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FLAW GROWTH BEHAVIOR IN THICK WELDED PLATES OF 2219-T87 ALUMINUM AT ROOM AND CRYOGENIC TEMPERATURES

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16. Abstract

Mechanical properties and axial load fatigue and fracture tests were conducted on thick welded plates of 2219-T87 aluminum alloy. The test objectives were to determine the tensile strength properties and the flaw growth behavior in electron beam, gas metal arc, and pulse current gas tungsten arc welds for plates 6.35 centimeters (2.5 in.) thick. The tests were conducted in room temperature air and in liquid nitrogen environments. Specimens were tested in both the as-welded and the aged after welding conditions. The experimental crack growth rate data were correlated with theoretical crack growth rate predictions for semielliptical surface flaws.

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FLAW GROWTH BEHAVIOR IN THICK WELDED PLATES OF 2219-T87 ALUMINUM AT ROOM AND CRYOGENIC TEMPERATURES

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SUMMARY

Smooth tensile specimens and surface-cracked fatigue and fracture specimens for three types of welds in thick aluminum plate were tested to determine mechanical properties and flaw growth behavior. Specimens were tested in both the as-welded and aged after welding conditions. For all three types of welds, aging after welding increased the tensile yield strength but decreased the fracture toughness. In the as-welded condition, the electron beam and pulse current gas tungsten arc weld specimens had higher toughness values than the gas metal arc weld specimens. After aging, the pulse current gas tungsten arc weld specimens had the highest toughness values. The fatigue crack growth rate for weld specimens was generally greater than for previously tested base metal specimens, and the growth rate experimental data compared favorably with analytical results.

INTRODUCTION

One of the many alternatives considered for the first stage of the space shuttle was a pressure-fed booster in which liquid oxygen and liquid propane propellants were used. The large diameter of 8.2 meters (27 ft) and the high internal tank pressure of 2.76 MN/m^2 (400 psi) necessitated tank wall thicknesses greater than anything that previously had been built. A fabrication feasibility assessment was therefore undertaken at the NASA Lyndon B. Johnson Space Center (JSC) for three materials: 2219-T87 aluminum alloy, Inconel 718, and 200 grade maraging steel. The investigation included preliminary assessments concerning potential problems in the areas of welding, forging, machining, roll forming, heat treatment, corrosion, fracture toughness, and mechanical properties.

Areas in which data were necessary but were almost completely lacking were fracture toughness, fatigue flaw growth rates, and mechanical properties of thick welds in 2219-T87 aluminum and Inconel 718. The data were required in order to evaluate weldability, to determine flaw detection requirements, to determine weld-land dimensions, and to estimate proof test requirements for preventing failures at operating pressure levels. The testing that was undertaken during the spring of 1972 to obtain experimental data relating to tensile properties, fracture toughness, and fatigue flaw growth behavior of welds in thick 2219-T87 aluminum plate is discussed in this report. Correlation of the fatigue crack growth rates with analytical predictions is also included.

The experimental results were determined for three types of weld techniques: electron beam (EB), gas metal arc (GMA), and pulse current gas tungsten arc (pulse GTA). The tests were conducted on specimens left in the as-welded condition and on specimens that were aged after welding. The test environments were room temperature (RT) air and liquid nitrogen (LN_2). With one exception, all weld joints were perpendicular to the longitudinal (loaded) axis of the specimens. The one exception was an EB welded flaw growth specimen with the weld running along the longitudinal centerline of the specimen.

SYMBOLS

The International System (SI) unit conversion factors used with these symbols are listed in the appendix.

A crack depth, centimeters (in.)

B crack half-length, centimeters (in.)

$\overline{CA}$ material constant for crack growth in the A-direction

E modulus of elasticity, GN/m^2 (10^6 psi)

F correction factor for the effect of the cracked plate surface (front face) on the growth of a crack through the thickness

F_{TU} ultimate tensile strength, MN/m^2 (ksi)

F_{TY} tensile yield strength (0.2-percent offset), MN/m^2 (ksi)

K stress intensity factor, $MN/m^{3/2}$ $\left(\text{ksi}\sqrt{\text{in.}}\right)$

K_A stress intensity factor at the minor axis of the semielliptical crack, $MN/m^{3/2}$ $\left(\text{ksi}\sqrt{\text{in.}}\right)$

K_{IC} critical stress intensity factor for fracture, $MN/m^{3/2}$ $\left(\text{ksi}\sqrt{\text{in.}}\right)$

M correction factor for the effect of crack shape and depth on the growth of a crack through the thickness

N number of fatigue load cycles

Q flaw shape correction factor

R ratio of minimum applied stress to maximum applied stress in a fatigue cycle

S numerical exponent in the fatigue crack growth equation

T plate thickness, millimeters (in.)

W specimen width, millimeters (in.)

ΔK_A stress intensity factor range at the minor axis during a fatigue cycle, $MN/m^{3/2}$ $\left(ksi\sqrt{in.}\right)$

$\Delta\sigma$ stress range during a fatigue cycle, maximum σ minus minimum σ, MN/m^2 (ksi)

θ angular coordinate

σ applied stress, MN/m^2 (ksi)

Φ complete elliptic integral of the second type

Subscripts:

avg. average conditions for N cycles

c conditions at failure

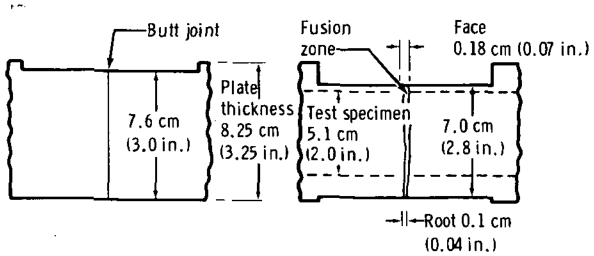
f final conditions after N cycles

i initial conditions before N cycles

TEST SPECIMEN DESCRIPTION

The 2219-T87 aluminum alloy used in the test program was obtained from Apollo Program surplus material. The material consisted of five plates, each 8.25 centimeters thick by 229 centimeters wide by 279 centimeters long (3-1/4 by 90 by 110 in.). The plates were machined, welded, and cut into 31 smaller plates that were then shipped to the JSC for the test specimens to be made. Thirty of the plates were used to make specimens with the welds perpendicular to the longitudinal (loaded) axis of the specimens (referred to as cross-weld specimens). The size of the cross-welded plates was 7.62 by 83.8 by 101.6 centimeters (3 by 33 by 40 in.), with the welds along the 83.8-centimeter (33 in.) width. The extra welded plate was 7.62 by 38.1 by 83.8 centimeters (3 by 15 by 33 in.) in size and was used to make a single specimen with the weld centrally located along the longitudinal axis (referred to as a longitudinal weld specimen).

The welding processes selected were based on past experience and on available technology for welding thick aluminum alloy plates. Electron beam, gas metal arc, and pulse current gas tungsten arc processes were selected. The welding contractor developed all weld procedures used in the program and provided all facilities for doing the welding. The joint configuration and weld parameters for the plates for the three types of welds are shown in figures 1, 2, and 3.

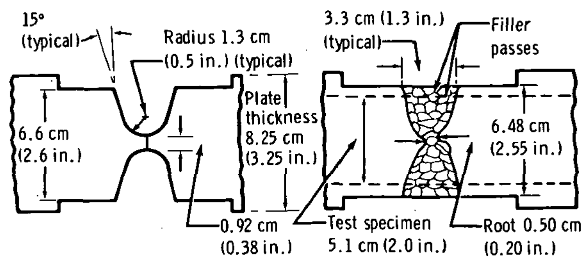


(a) Before welding.

(b) After welding and cleanup machining.

Material:	2219-T87 aluminum alloy
Process:	EB
Power:	24.5-kilovolt potential, 374-milliampere beam current
Sequence:	Single pass; travel: 150 cm/min (60 in/min)
Filler metal:	Wire (0.16-cm (0.063 in.) diameter) of 2319 alloy added at face to prevent concavity
Remarks:	1. Joint scraped before welding 2. Cleanup machining (crown and drop-through removal) done to facilitate inspection and to remove root porosity

Figure 1. - Joint configuration and weld parameters for 2219-T87 aluminum EB welds.



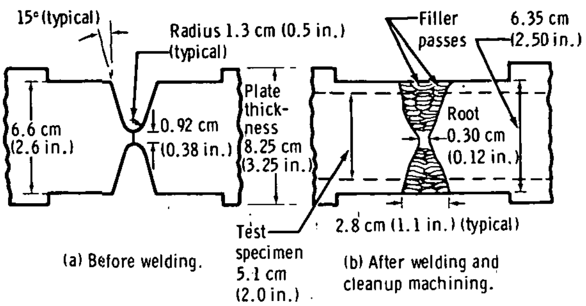
(a) Before welding.

(b) After welding and cleanup machining.

Material:	2219-T87 aluminum alloy
Process:	Pulse GTA (20-kHz pulse frequency) and GMA
Filler metal:	Wire (0.16-cm (0.063 in.) diameter) of 2319 alloy; feed: 150 cm/min (60 in/min) typical
Sequence:	1. Root pass, free fall; no filler; travel: 20 cm/min (8 in/min); power: 300 amperes, 11.5 volts; pulse GTA 2. Cap pass at root (with filler); travel: 20 cm/min (8 in/min); power: 250 amperes, 12 volts; pulse GTA 3. Fill "U" grooves with approximately 34 passes; travel: 36 cm/min (14 in/min); power: 530 to 585 amperes, 24 to 27 volts; GMA
Remarks:	1. Joint scraped before welding 2. Joint wire brushed and vacuumed after each weld pass 3. Interpass temperature 380° K (225° F) maximum 4. Sequence of filler passes: two passes per side to sixth pass; four passes per side to 14th pass; six passes per side to 34th pass 5. Cleanup machining (crown removal) done to facilitate inspection

Figure 2. - Joint configuration and weld parameters for 2219-T87 aluminum GMA welds.

The welding of 2219-T87 aluminum alloy in thicknesses greater than 5.1 centimeters (2.0 in.) has rarely been accomplished or required in the past. As a result, little experience was available to assist in establishing the weld parameters for the selected processes (EB, GMA, and pulse GTA). In addition, because of the limited material and time available for developing the parameters, the weld contractor was unable to establish the optimum welding procedures for producing consistent aerospace quality structural welds.



Material: 2219-T87 aluminum alloy

Process: Pulse GTA (20-kHz pulse frequency)

Filler metal: Wire (0.16-cm (0.063 in.) diameter) of 2319 alloy; feed: 150 cm/min (60 in/min) typical

Sequence:
1. Root pass, free fall; no filler; travel: 20 cm/min (8 in/min); power: 300 amperes, 11.5 volts
2. Cap pass at root (with filler); travel: 20 cm/min (8 in/min); power: 250 amperes, 12 volts
3. Fill "U" grooves with approximately 55 passes; travel: 180 cm/min (71 in/min); power: 250 to 325 amperes, 13.5 volts

Remarks:
1. Joint scraped before welding
2. Joint wire brushed and vacuumed after each weld pass
3. Interpass temperature 390° K (240° F) maximum
4. Sequence of filler passes: three passes per side to 19th pass; four passes per side to 55th pass
5. Cleanup machining (crown removal) done to facilitate inspection

Figure 3. - Joint configuration and weld parameters for 2219-T87 aluminum pulse GTA welds.

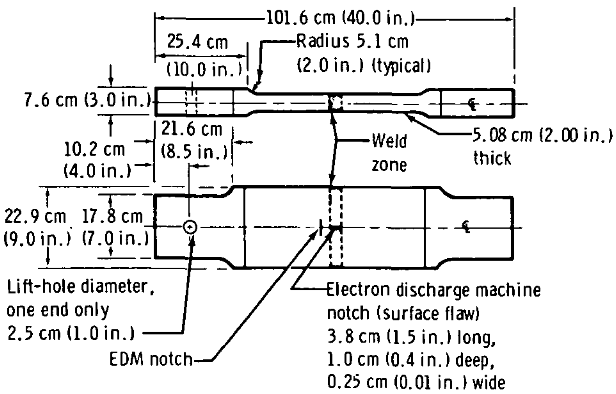
The EB welds generally exhibited significant porosity defects in the weld root area. The basic weld thickness was 7.6 centimeters (3.0 in.), and difficulty was experienced in obtaining full penetration in a single pass by the use of the maximum output power (9.2 kW) from the available EB welding equipment. To compensate for material loss at the face of the weld resulting from the use of high beam power, sufficient filler metal of the same alloy was added during welding to fill any concavities formed in the weld face. After welding, cleanup machining was done to remove the significant porosity at the weld root, to remove the filler metal concentration at the weld face, and to facilitate radiographic inspection of the weld zone of each plate.

The GMA welds produced for this study (fig. 2) were actually dual-process welds. The joint root was welded by means of the pulse GTA process at the recommendation of the welding contractor. After the root weld was completed, the conventional GMA process was used to complete the weld. The weld faces were machined flush to remove the weld crowns for facilitation of radiographic inspection.

The pulse GTA welding process is similar to the conventional GTA process, except that the weld current is pulsed from low to high levels at a high cyclic frequency. Pulse GTA welding has been reported to produce better weld properties because of the resulting finer grain structure and fewer defects (porosity, cracks, etc.) than the conventional (nonpulsed) GTA welding. As a result of these reported advantages, the welding contractor used the pulse GTA weld process for all GTA welding requirements. All pulse GTA welding in this study was done at a pulse frequency of 20 kilohertz.

After the plates were welded and the weld faces were machined, the plates were shipped to the JSC for machining into test specimens and for aging heat treatment. Of the 30 large plates that were shipped and machined into specimens, 12 were EB welded, 12 were GMA welded, and six were pulse GTA welded. The one small plate for the longitudinal weld fatigue specimen was EB welded.

Out of each of the 30 large plates, three 22.9-centimeter (9.0 in.) wide cross-weld fracture specimens were machined in accordance with the drawing in figure 4. Bars from which weld tensile specimens were machined also were cut from the 30 plates. Two types of tensile specimens were machined from the bars. The first



Material: 2219-T87 aluminum alloy plate

Weld process/joint configuration:

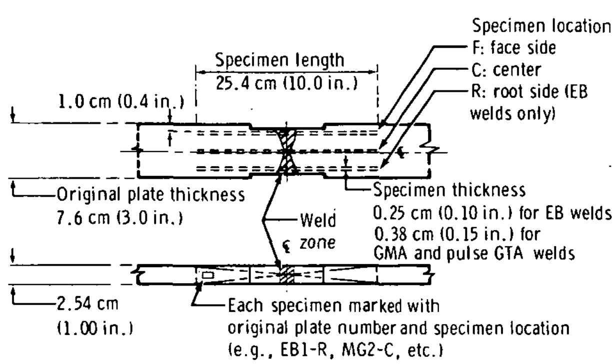
1. EB/butt joint (fig. 1)
2. GMA/modified double "U" joint (fig. 2)
3. Pulse GTA/modified double "U" joint (fig. 3)

Figure 4. - Surface flaw cross-weld fracture specimen.

type, a partial-cross-section tensile specimen, is shown in figure 5; its purpose was to determine the weld strength at three locations through the thickness of the plate. The second type, a full-cross-section tensile specimen, is shown in figure 6. It has almost the same thickness as the welded plate from which it was cut. The purpose of the full-cross-section tensile specimens was to determine the gross strength properties of the thick welded plate.

After final machining, the aging heat treatment performed on some of the specimens was done at 435.9° K (325° F) for 24 hours in a circulating-air-type furnace. However, more than half the specimens were left in the as-welded condition.

For the complete program, a total of 82 surface-flawed specimens, 21 full-cross-section tensile specimens, and 50 partial-cross-section tensile specimens was used. (Only nine of the 12 GMA welded plates were machined into specimens and tested.) For each of these three types of specimens, approximately half were tested in air at room temperature and half were tested in liquid nitrogen.

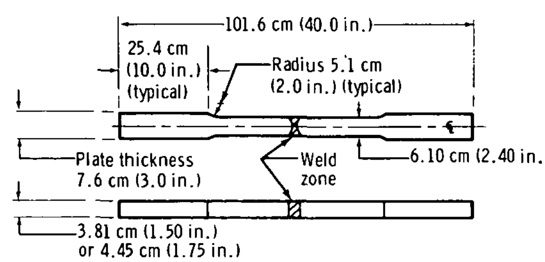


Material: 2219-T87 aluminum alloy plate

Weld process/ joint configuration:

1. EB/butt joint (fig. 1)
2. GMA/modified double "U" joint (fig. 2)
3. Pulse GTA/modified double "U" joint (fig. 3)

Figure 5. - Location of partial-cross-section aluminum tensile specimens.



Material: 2219-T87 aluminum alloy plate

Weld process/joint configuration:

1. EB/butt joint (fig. 1)
2. GMA/modified double "U" joint (fig. 2)
3. Pulse GTA/modified double "U" joint (fig. 3)

Figure 6.- Full-cross-section aluminum tensile specimens.

TEST APPARATUS AND PROCEDURES

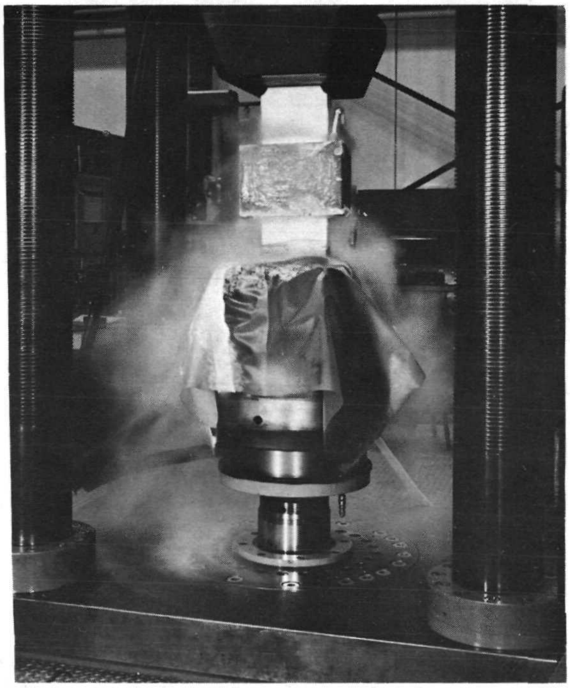
The testing of the 2219 aluminum alloy welded specimens was conducted at room temperature and in liquid nitrogen to obtain the following weld properties.

1. Tensile properties (F_{TU}, F_{TY}, E) of the welds in full-cross-section and partial-cross-section specimens

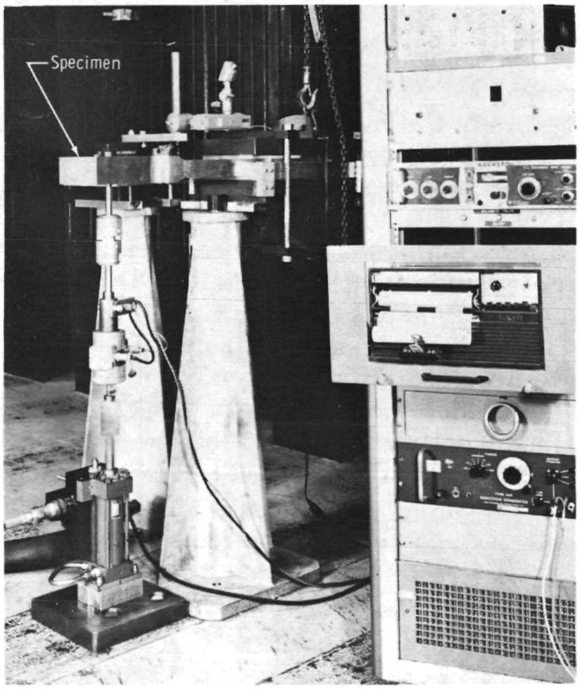
2. Critical stress intensity factor for fracture K_{IC} of welds in thick plate

3. Crack growth rates dA/dN of surface-flawed welds in thick plate

Except for the tests with the partial-cross-section specimens, all testing was conducted using a 272 000-kilogram (600 000 lb) capacity hydraulically operated axial-load fatigue testing machine. The loads were applied through self-alining hydraulically operated friction grips. The tension tests on the partial-cross-section specimens were done on a smaller 4500-kilogram (10 000 lb) capacity tensile testing machine. The cryogenic tests were conducted by installing an open-top polyurethane foam box around the specimens and maintaining the container full of liquid nitrogen. Approximately 20 minutes of soaking time was required to stabilize the specimen at LN_2 temperature before each test. A photograph of an LN_2 fracture test is shown in figure 7(a).



(a) LN_2 fracture test.



(b) Specimen precracking setup.

Figure 7. - The LN_2 fracture test and specimen precracking setup.

To initiate fatigue cracks in the surface-flawed specimens, the specimens were notched with an electron discharge machine (EDM) and cracks were then grown from the notches by subjecting the specimens to bending fatigue. The machined notches were approximately 3.8 centimeters (1.5 in.) long and 1.0 centimeter (0.4 in.) deep. The precracking was done at a load ratio R of 0.1 and a maximum load such that a fatigue crack 1.27 centimeters (0.5 in.) long developed on each end of the notch in an average of 160 000 cycles. Thus, the growth rate for precracking was very low and was less than any measured in the subsequent growth rate tests. The specimens were therefore not preconditioned in any way because of prestressing. A photograph of a specimen being precracked is shown in figure 7(b).

Initially, precracked fracture specimens for each type of weld were pulled to failure to obtain fracture toughness values. Later, most specimens first were axially fatigue tested at given load levels and number of cycles and then were pulled to failure. By the application of low stress cycles, then higher stress cycles, then low stress cycles again, two growth rate data points, along with retardation effect data and a fracture toughness value for each specimen, were obtained.

The tensile yield strength for the weld material was obtained from strain gages on the tensile specimens. The strain gage lengths were approximately one-half the width of the welds. The gages were installed back-to-back on the faces of the specimens, and the strain readings were averaged to cancel bending effects.

RESULTS AND DISCUSSION

Metallography and Hardness Measurements

In the metallography study, the three types of weld specimens (EB, GMA, and pulse GTA) were sectioned, polished, and etched to show the weld. Photographs of these sections are shown in figures 8 to 13. The photographs of the weld sections show that the EB and GMA welds were essentially without defect. However, subsequent examination of the fractured surfaces of the EB weld test specimens showed cylindrical voids and insufficient melting in the weld root. The photograph of the pulse GTA weld (fig. 10) shows a crack resulting from lack of fusion at a depth of approximately one-fourth the thickness of the plate. At this location, two passes were used to cover the width of the joint. After the problem had been discussed with the welding contractor, it was determined that the weld joint on the first pulse GTA welded plate was machined incorrectly. The weld joint was 0.5 centimeter (0.2 in.) wider than required, which undoubtedly contributed to the lack-of-fusion crack. However, this welding defect did not appear to influence the fracture toughness and crack growth data obtained from these specimens (PT1 specimens). Rockwell hardness traverse measurements were conducted on the specimen sections, and the results are also shown in the figures. Hardness readings for the as-welded condition are shown in figures 8, 9, and 10; hardness readings for the aged after welding condition are shown in figures 11, 12, and 13. The results of the hardness measurements show that postweld aging significantly increased the hardness of the weld material, but the effect on the hardness of the base metal was negligible.

0.5 cm (0.2 in.)

1.27 cm (0.5 in.)

						Weld ℄							
80.7	79.3	79.4	78.8	77.3	66.2	29.2	59.2	74.7	79.2	79.6	79.2	80.3	79.8
80.4	80.5	80.0	79.6	78.9	66.2	29.4	62.5	78.1	78.2	79.2	79.2	78.7	78.5
80.0	80.0	79.4	78.9	79.0	66.3	28.9	63.8	77.9	78.5	79.4	79.6	80.1	79.4
79.7	79.7	79.0	79.0	78.9	69.7	31.1	70.6	78.1	78.2	78.7	79.4	79.3	80.2
78.3	79.0	78.5	79.5	79.1	77.9	33.3	80,0	79.6	80.0	80.2	80.2	80.8	-

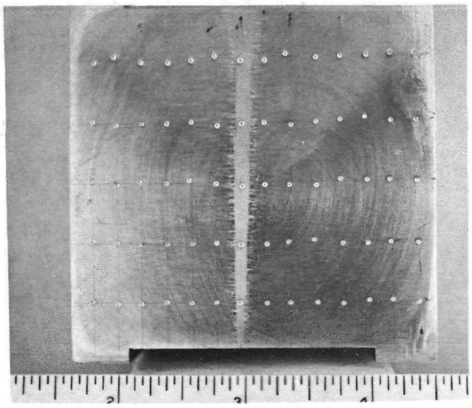


Figure 8. - Full-cross-section photograph and Rockwell hardness readings for EB welded 2219-T87 aluminum alloy (as welded).

0.51 cm (0.2 in.)

1.27 cm (0.5 in.)

						Weld ℄							
79.4	75.5	65.3	44.6	14.0	11.3	24.1	-	22.4	39.3	62.8	74.3	77.2	78.7
79.5	79.1	78.1	48.5	12.7	19.6	20.3	16.5	20.2	48.7	65.3	77.7	78.3	78.7
80.3	80.5	81.2	79.5	73.8	55.8	42.0	55.5	64.8	-	-	79.6	79.6	78.9
78.8	79.5	79.3	69.8	44.2	26.2	21.4	30.3	21.9	31.0	51.2	67.3	79.0	78.1
79.1	75.8	65.7	45.7	24.0	18.2	15.5	20.0	13.2	-	43.0	67.8	76.7	78.1

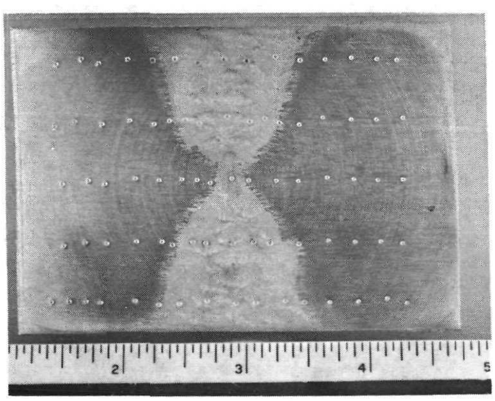


Figure 9. - Full-cross-section photograph and Rockwell hardness readings for GMA welded 2219-T87 aluminum alloy (as welded).

0.5 cm
(0.2 in.)

Weld ℄

Row spacing: 1.0 cm (0.40 in.); 1.9 cm (0.75 in.); 1.27 cm (0.50 in.); 1.27 cm (0.50 in.)

						℄							
77.9	74.3	64.8	46.0	19.7	21.0	22.6	25.9	26.8	44.8	65.7	74.7	78.3	79.0
78.2	77.9	75.6	65.7	39.5	29.3	24.6	26.7	41.5	68.3	76.0	78.0	77.9	78.3
79.0	79.5	79.8	79.0	74.8	50.0	41.2	49.9	71.8	78.0	78.2	78.0	73.2	77.1
78.6	78.5	77.1	69.8	67.1	41.5	32.2	35.5	31.0	42.0	70.0	76.5	78.2	78.2
77.8	75.8	67.7	47.5	26.1	25.8	22.2	24.9	24.2	43.8	63.2	74.0	76.8	77.9

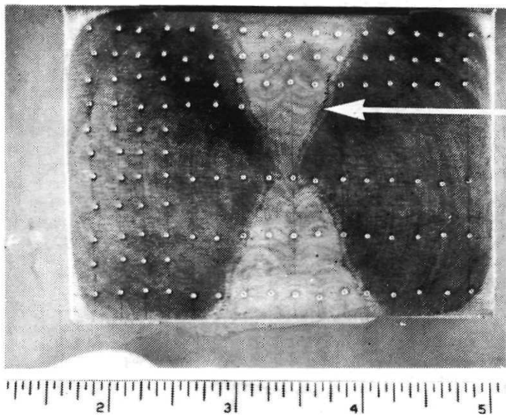


Figure 10. - Full-cross-section photograph and Rockwell hardness readings for pulse GTA welded 2219-T87 aluminum alloy (as welded), showing crack in top half of weld.

0.5 cm
(0.2 in.)

Weld ℄

Row spacing: 1.9 cm (0.75 in.)

						℄						
79.2	78.2	78.0	77.9	77.5	65.0	41.9	67.0	77.3	77.9	78.0	78.3	78.3
78.6	78.0	78.6	77.9	77.4	64.1	45.0	69.5	76.4	77.4	78.3	78.0	78.6
78.5	78.5	78.9	78.4	77.8	71.7	51.0	76.8	77.9	78.4	77.6	78.2	78.2

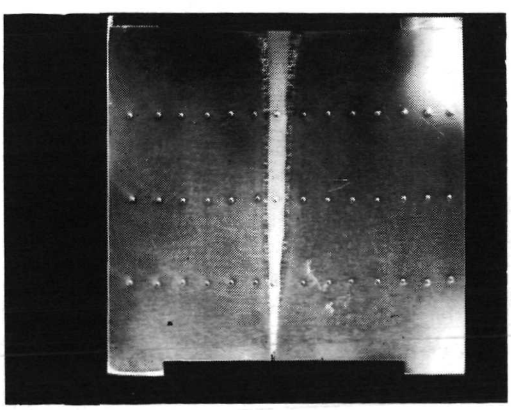


Figure 11. - Full-cross-section photograph and Rockwell hardness readings for EB welded 2219-T87 aluminum alloy (aged after welding).

0.5 cm
(0.2 in.)

Weld
℄

1.9 cm
(0.75 in.)

77.9	77.5	76.8	59.8	37.5	30.3	30.7	24.3	36.1	59.8	75.7	77.2	76.6
79.0	78.7	79.5	79.4	74.8	61.2	52.3	55.2	74.8	78.2	78.3	77.8	77.3
78.0	78.0	75.9	57.5	37.2	32.5	38.7	36.3	40.5	65.2	77.5	78.4	77.9

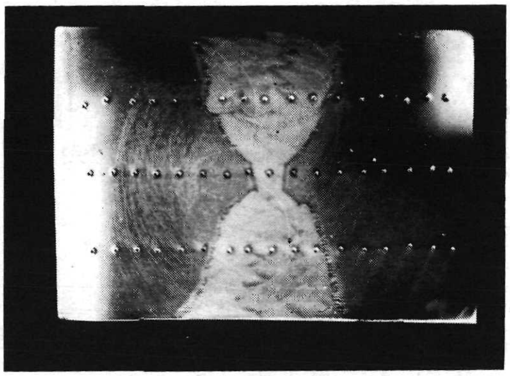


Figure 12. - Full-cross-section photograph and Rockwell hardness readings for GMA welded 2219-T87 aluminum alloy (aged after welding).

0.5 cm
(0.2 in.)

Weld
℄

1.9 cm
(0.75 in.)

76.2	76.0	72.3	64.8	58.6	41.3	47.6	45.8	47.5	69.0	75.8	76.3	75.8
76.3	76.5	77.5	77.3	69.8	52.4	50.4	58.5	75.3	76.7	77.4	77.5	76.1
76.0	75.8	75.6	67.5	42.5	45.8	41.3	47.6	42.6	68.7	76.2	76.0	75.7

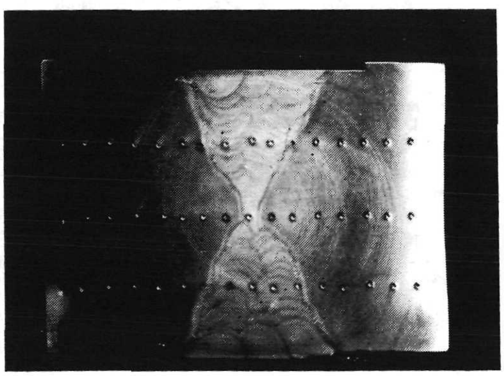


Figure 13. - Full-cross-section photograph and Rockwell hardness readings for pulse GTA welded 2219-T87 aluminum alloy (aged after welding).

The results of microhardness traverse measurements midway through the thickness of an unaged EB weld section are shown in figure 14. As expected, the results show that the heat-affected zone for an EB weld is relatively small. The joint attained full hardness at approximately 0.75 centimeter (0.3 in.) from the weld fusion line.

Tensile Strength Tests

A total of 71 cross-welded specimens consisting of 50 partial-cross-section specimens (fig. 5) and 21 full-cross-section specimens (fig. 6) was tested to obtain tensile strength data. A summary of the tensile yield strength results is listed in table I. The complete results (F_{TU}, F_{TY}, and E) for the partial-cross-section specimens are listed in tables II to IV, and the results of the full-cross-section specimens are listed in table V.

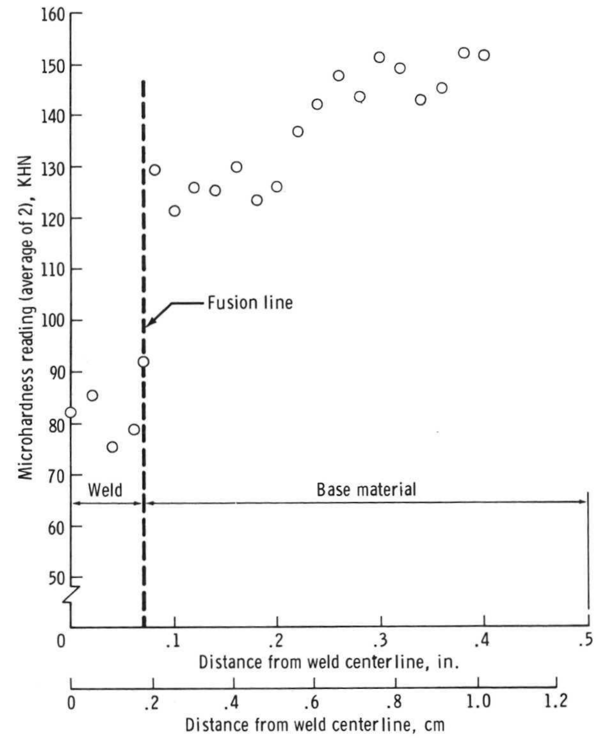


Figure 14.- Microhardness readings compared to distance from weld centerline for section of unaged EB weld specimen.

TABLE I.- SUMMARY OF TENSILE YIELD STRENGTH RESULTS FOR 2219-T87 ALUMINUM WELDS

F_{TY} for partial-cross-section specimens of the weld face, MN/m^2 (ksi)				F_{TY} for partial-cross-section specimens of the weld center, MN/m^2 (ksi)				F_{TY} for full-cross-section specimens, MN/m^2 (ksi)			
As welded		Postweld aged		As welded		Postweld aged		As welded		Postweld aged	
RT	LN_2	RT	LN_2	RT	LN_2	RT	LN_2	RT	LN_2	RT	LN_2
EB welds											
120.0 (17.4)	148.2 (21.5)	162.7 (23.6)	242.0 (35.1)	140.0 (20.3)	190.3 (27.6)	206.8 (30.0)	224.1 (35.4)	Not measured			
115.8 (16.8)	144.8 (21.0)	166.2 (24.1)	--	150.3 (21.8)	203.4 (29.5)	210.3 (30.5)	277.9 (40.3)				
GMA welds											
127.6 (18.5)	151.7 (22.0)	140.7 (20.4)	219.3 (31.8)	180.6 (26.2)	206.8 (30.0)	180.6 (26.2)	297.9 (43.2)	139.3 (20.2)	164.1 (23.8)	166.9 (24.2)	203.4 (29.5)
122.7 (17.8)	156.5 (22.7)	--	224.1 (32.5)	171.7 (24.9)	--	--	--	128.2 (16.6)	176.5 (25.6)	176.5 (25.6)	186.2 (27.0)
125.5 (18.2)	--	--	--	--	--	--	--	--	--	--	--
115.1 (16.7)	--	--	--	--	--	--	--	--	--	--	--
High-frequency pulse GTA welds											
127.6 (18.5)	160.6 (23.3)	201.3 (29.2)	215.8 (31.3)	173.7 (25.2)	224.1 (32.5)	203.4 (29.5)	283.4 (41.1)	124.1 (18.0)	197.9 (28.7)	177.9 (25.8)	196.5 (28.5)
135.1 (19.6)	173.7 (25.2)	184.8 (26.8)	201.3 (29.2)	184.1 (26.7)	--	--	--	149.6 (21.7)	--	--	--
129.6 (18.8)	--	--	--	--	--	--	--	--	--	--	--
131.7 (19.1)	--	--	--	--	--	--	--	--	--	--	--

TABLE II. - PARTIAL-CROSS-SECTION-SPECIMEN TENSILE TEST RESULTS FOR 6.35-CENTIMETER (2.5 IN.)

THICK 2219-T87 ALUMINUM ELECTRON BEAM WELDS

Specimen number	Test environment	Specimen width, cm (in.)	Specimen thickness, cm (in.)	E, GN/m^2 (10^6 psi)	F_{TY}, MN/m^2 (ksi)	F_{TU}, MN/m^2 (ksi)
EB1-R[a]	RT[b]	2.606 (1.026)	0.287 (0.113)	--	--	191.7 (27.8)
EB1-C[c]	RT	2.601 (1.024)	.295 (.116)	73.8 (10.7)	140.0 (20.3)	285.4 (41.4)
EB1-F[d]	RT	2.581 (1.016)	.279 (.110)	74.5 (10.8)	120.0 (17.4)	268.9 (39.0)
EB2-R	RT	2.570 (1.012)	.292 (.115)	--	--	164.1 (23.8)
EB2-C	RT	2.598 (1.023)	.305 (.120)	68.3 (9.9)	150.3 (21.8)	283.3 (41.1)
EB2-F	RT	2.598 (1.023)	.300 (.118)	63.4 (9.2)	115.8 (16.8)	266.8 (38.7)
EB3-R	RT	2.570 (1.012)	.295 (.116)	--	--	132.4 (19.2)
EB3-C	LN_2[e]	2.570 (1.012)	.295 (.116)	84.1 (12.2)	190.3 (27.6)	406.1 (58.9)
EB3-F	LN_2	2.555 (1.006)	.292 (.115)	83.4 (12.1)	148.2 (21.5)	367.5 (53.3)
EB4-R	RT	2.558 (1.007)	.297 (.117)	--	--	149.6 (21.7)
EB4-C	LN_2	2.550 (1.004)	.302 (.119)	77.9 (11.3)	203.4 (29.5)	350.9 (50.9)
EB4-F	LN_2	2.532 (.997)	.284 (.112)	91.0 (13.2)	144.8 (21.0)	412.3 (59.8)
EB5C-A[f]	RT	2.522 (.993)	.292 (.115)	75.8 (11.0)	206.8 (30.0)	321.3 (46.6)
EB5F-A	RT	2.504 (.986)	.295 (.116)	75.2 (10.9)	162.7 (23.6)	304.1 (44.1)
EB6R-A	RT	2.576 (1.014)	.302 (.119)	--	--	328.2 (47.6)
EB6C-A	LN_2	2.570 (1.012)	.292 (.115)	81.4 (11.8)	244.1 (35.4)	457.8 (66.4)
EB6F-A	RT	2.548 (1.003)	.282 (.111)	74.5 (10.8)	166.2 (24.1)	310.3 (45.0)
EB7R-A	RT	2.558 (1.007)	.305 (.120)	--	--	161.3 (23.4)
EB7C-A	LN_2	2.543 (1.001)	.292 (.115)	80.0 (11.6)	277.9 (40.3)	472.3 (68.5)
EB7F-A	LN_2	2.553 (1.005)	.295 (.116)	82.7 (12.0)	242.0 (35.1)	435.1 (63.1)
EB11C-A	RT	2.555 (1.006)	.384 (.151)	73.1 (10.6)	210.3 (30.5)	305.4 (44.3)

[a]"R" in specimen number refers to root of weld.

[b]RT denotes room temperature exposure in air at 294° K (70° F).

[c]"C" in specimen number refers to center of weld.

[d]"F" in specimen number refers to face of weld.

[e]LN_2 denotes liquid nitrogen exposure at 77.6° K (-320° F).

[f]Specimens ending in "A" were postweld aged for 24 hours at 436° K (325° F).

TABLE III. - PARTIAL-CROSS-SECTION-SPECIMEN TENSILE TEST RESULTS FOR 6.35-CENTIMETER (2.5 IN.) THICK 2219-T87 ALUMINUM GAS METAL ARC WELDS

Specimen number	Test environment	Specimen width, cm (in.)	Specimen thickness, cm (in.)	E, GN/m^2 (10^6 psi)	F_{TY}, MN/m^2 (ksi)	F_{TU}, MN/m^2 (ksi)
MG1F-1[a]	RT[b]	2.592 (1.021)	0.374 (0.147)	70.3 (10.2)	127.6 (18.5)	225.5 (32.7)
MG1C[c]	RT	2.581 (1.016)	.371 (.146)	75.8 (11.0)	180.6 (26.2)	300.6 (43.6)
MG1F-2	RT	2.563 (1.009)	.371 (.146)	67.6 (9.8)	122.7 (17.8)	195.8 (28.4)
MG3F-1	RT	2.593 (1.021)	.376 (.148)	67.6 (9.8)	125.5 (18.2)	209.6 (30.4)
MG3C	RT	2.569 (1.011)	.374 (.147)	69.6 (10.1)	171.7 (24.9)	292.3 (42.4)
MG3F-2	RT	2.562 (1.009)	.371 (.146)	68.3 (9.9)	115.1 (16.7)	233.0 (33.8)
MG4F-1	LN_2[d]	2.540 (1.000)	.376 (.148)	81.4 (11.8)	151.7 (22.0)	228.2 (33.1)
MG4C	LN_2	2.542 (1.001)	.374 (.147)	84.1 (12.2)	206.8 (30.0)	338.5 (49.1)
MG4F-2	LN_2	2.534 (.998)	.368 (.145)	80.0 (11.6)	156.5 (22.7)	218.6 (31.7)
MG5F-1A[e]	RT	2.533 (.997)	.376 (.148)	66.9 (9.7)	140.7 (20.4)	276.5 (40.1)
MG5C-A	RT	2.533 (.997)	.376 (.148)	57.9 (8.4)	180.6 (26.2)	324.7 (47.1)
MG11F-1A	LN_2	2.560 (1.008)	.358 (.141)	82.7 (12.0)	219.3 (31.8)	304.7 (44.2)
MG11C-A	LN_2	2.560 (1.008)	.365 (.144)	82.7 (12.0)	297.9 (43.2)	453.7 (65.8)
MG11F-2A	LN_2	2.540 (1.000)	.360 (.142)	79.3 (11.5)	224.1 (32.5)	268.9 (39.0)

[a]"F" in specimen number refers to face of weld.

[b]RT denotes room temperature exposure in air at 294° K (70° F).

[c]"C" in specimen number refers to center of weld.

[d]LN_2 denotes liquid nitrogen exposure at 77.6° K (-320° F).

[e]Specimens ending in "A" were postweld aged for 24 hours at 436° K (325° F).

TABLE IV. - PARTIAL-CROSS-SECTION-SPECIMEN TENSILE TEST RESULTS FOR 6.35-CENTIMETER (2.5 IN.) THICK 2219-T87 ALUMINUM HIGH-FREQUENCY PULSE CURRENT GAS TUNGSTEN ARC WELDS

Specimen number	Test environment	Specimen width, cm (in.)	Specimen thickness, cm (in.)	E, GN/m^2 (10^6 psi)	F_{TY}, MN/m^2 (ksi)	F_{TU}, MN/m^2 (ksi)
PT2F[a]	RT[b]	2.595 (1.022)	0.376 (0.148)	68.3 (9.9)	127.6 (18.5)	268.2 (38.9)
PT2C[c]	RT	2.591 (1.020)	.376 (.148)	75.2 (10.9)	173.7 (25.2)	307.5 (44.6)
PT2F-2	RT	2.583 (1.017)	.360 (.144)	73.1 (10.6)	135.1 (19.6)	283.4 (41.1)
PT3F-1	RT	2.583 (1.017)	.363 (.143)	74.5 (10.8)	129.6 (18.8)	264.1 (38.3)
PT3C	RT	2.578 (1.015)	.376 (.148)	72.4 (10.5)	184.1 (26.7)	308.9 (44.8)
PT3F-2	RT	2.570 (1.012)	.368 (.145)	73.1 (10.6)	131.7 (19.1)	263.4 (38.2)
PT4F-1	LN_2[d]	2.527 (.995)	.373 (.147)	82.7 (12.0)	160.6 (23.3)	377.1 (54.7)
PT4C	LN_2	2.543 (1.001)	.373 (.147)	82.0 (11.9)	224.1 (32.5)	426.1 (61.8)
PT4F-2	LN_2	2.543 (1.001)	.363 (.143)	87.6 (12.7)	173.7 (25.2)	376.4 (54.6)
PT5F-1A[e]	RT	2.543 (1.001)	.366 (.144)	84.1 (12.2)	201.3 (29.2)	308.9 (44.8)
PT5C-A	RT	2.548 (1.003)	.361 (.142)	75.8 (11.0)	203.4 (29.5)	304.7 (44.2)
PT5F-2A	RT	2.553 (1.005)	.356 (.140)	74.5 (10.8)	184.8 (26.8)	307.5 (44.6)
PT6F-1A	LN_2	2.550 (1.004)	.363 (.143)	78.6 (11.4)	215.8 (31.3)	231.0 (33.5)
PT6C-A	LN_2	2.578 (1.015)	.371 (.146)	85.5 (12.4)	283.4 (41.1)	439.2 (63.7)
PT6F-2A	LN_2	2.576 (1.014)	.361 (.142)	--	201.3 (29.2)	302.0 (43.8)

[a]"F" in specimen number refers to face of weld.

[b]RT denotes room temperature exposure in air at 294° K (70° F).

[c]"C" in specimen number refers to center of weld.

[d]LN_2 denotes liquid nitrogen exposure at 77.6° K (-320° F).

[e]Specimens ending in "A" were postweld aged for 24 hours at 436° K (325° F).

TABLE V. - FULL-CROSS-SECTION-SPECIMEN TENSILE TEST RESULTS FOR

6.35-CENTIMETER (2.5 IN.) THICK 2219-T87 ALUMINUM WELDS

Specimen number	Test environment	Specimen thickness, cm (in.)	Specimen width, cm (in.)	E, GN/m^2 (10^6 psi)	F_{TY}, MN/m^2 (ksi)	F_{TU}, MN/m^2 (ksi)
EB welds						
EB2-1[a]	LN_2[b]	6.383 (2.513)	4.475 (1.762)	--	--	253.7 (36.8)
EB3-1	RT[c]	6.248 (2.460)	4.496 (1.770)	79.3 (11.5)	--	335.1 (48.6)
EB4-1	LN_2	6.304 (2.482)	4.483 (1.765)	--	--	371.6 (53.9)
EB5-1	RT	6.281 (2.473)	4.509 (1.775)	86.9 (12.6)	--	275.8 (40.0)
EB1-A[d]	RT	6.340 (2.496)	4.595 (1.809)	--	--	282.7 (41.0)
EB2-A	LN_2	6.391 (2.516)	4.493 (1.769)	--	--	362.7 (52.6)
EB6-1A	RT	6.345 (2.498)	4.509 (1.775)	--	--	289.6 (42.0)
EB6-2A	LN_2	6.368 (2.507)	4.501 (1.772)	--	--	348.9 (50.6)
High-frequency pulse GTA welds						
PT2-A	RT	6.114 (2.407)	3.851 (1.516)	73.1 (10.6)	177.9 (25.8)	311.6 (45.2)
PT3-A	LN_2	6.035 (2.376)	3.846 (1.514)	100.7 (14.6)	196.5 (28.5)	375.8 (54.5)
PT4	LN_2	6.111 (2.406)	3.866 (1.522)	87.6 (12.7)	197.9 (28.7)	319.9 (46.4)
PT5	RT	5.657 (2.227)	3.856 (1.518)	71.0 (10.3)	124.1 (18.0)	312.3 (45.3)
PT6	RT	6.076 (2.392)	3.825 (1.506)	74.5 (10.8)	149.6 (21.7)	306.1 (44.4)
GMA welds						
MG1	RT	6.139 (2.417)	3.840 (1.512)	82.7 (12.0)	139.3 (20.2)	226.1 (32.8)
MG2	RT	6.139 (2.417)	3.848 (1.515)	66.2 (9.6)	128.2 (18.6)	203.4 (29.5)
MG3	LN_2	6.149 (2.421)	3.830 (1.508)	78.6 (11.4)	164.1 (23.8)	164.1 (38.3)
MG4	LN_2	6.106 (2.404)	3.835 (1.510)	80.7 (11.7)	176.5 (25.6)	256.5 (37.2)
MG5-A	RT	6.126 (2.412)	3.825 (1.506)	66.9 (9.7)	166.9 (24.2)	242.7 (35.2)
MG6-A	RT	6.132 (2.414)	3.815 (1.502)	68.9 (10.0)	176.5 (25.6)	262.0 (38.0)
MG7-A	LN_2	6.154 (2.423)	3.870 (1.524)	77.9 (11.3)	203.4 (29.5)	284.1 (41.2)
MG8-A	LN_2	6.106 (2.404)	3.832 (1.509)	77.9 (11.3)	186.2 (27.0)	213.0 (30.9)

[a]Specimen had significant porosity at weld root.

[b]LN_2 denotes liquid nitrogen exposure at 77.6° K (-320° F).

[c]RT denotes room temperature exposure in air at 294° K (70° F).

[d]Specimens ending with "A" were postweld aged for 24 hours at 436° K (325° F).

The following conclusions can be made regarding the tensile test results.

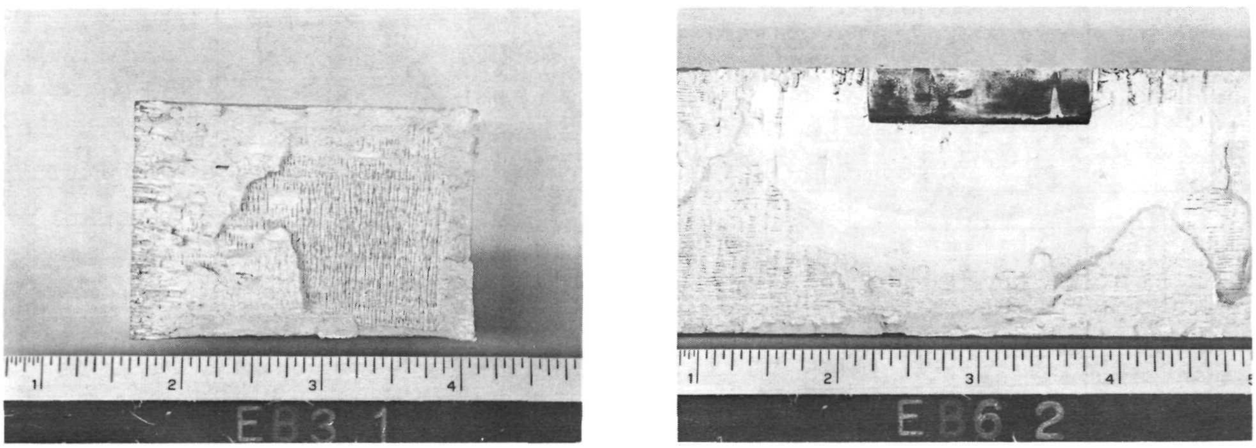
1. As expected, the weld strength was well below (from 43 to 71 percent) the typical ultimate strength reported in reference 1 for base material (469 MN/m^2 (68 ksi)).

2. The results from the partial-cross-section specimens showed that both yield and ultimate strength values for all three types of welds were greater at the weld center than at the weld face.

3. Both postweld aging and testing at LN_2 temperature increased the yield and ultimate strength properties, particularly for the EB weld specimens.

4. The ultimate strengths of the EB and pulse GTA welds were higher than for the GMA welds.

5. There was considerable scatter in the tensile test data, especially for the EB weld root and EB full-cross-section specimens. Although the metallography for the EB welds looked satisfactory, the strength and ductility of the weld root material was very low. This situation is shown in the data listed in table II and in figure 15, where weld defects and a lack of a shear lip can be seen at the weld root. As mentioned previously, the capacity of the EB welding equipment contributed to the weld root problem. If higher capacity equipment had been used, the EB weld strength would probably have been significantly greater than the strength of the pulse GTA welds.



(a) Tensile specimen EB3-1 (weld root at left).

(b) Fracture specimen EB6-2.

Figure 15. - Fracture face photographs of EB welded specimens.

Fracture Toughness Results

The fatigue crack growth and fracture data were analyzed using the stress intensity factor method. The calculations were made using the equation below for the stress intensity factor at the minor axis of a semielliptical surface-type flaw.

$$K_A = F\sigma\sqrt{\frac{\pi A}{Q}}\,M \tag{1}$$

where Q is a flaw shape correction factor given by the equation

$$Q = \Phi^2 - 0.212\left(\frac{\sigma}{F_{TY}}\right)^2 \tag{2}$$

and Φ is an elliptic integral of the second kind with the values listed in table VI.

TABLE VI. - VALUES OF Φ^2 AS A FUNCTION OF A/B

$$\left[\Phi = \int_0^{\pi/2} \left[1 - \left(\frac{B^2 - A^2}{B^2}\right)\sin^2\theta\right]^{1/2} d\theta\right]$$

A/B	Φ^2	A/B	Φ^2
0.00000	1.000000	0.74162	1.891730
.22361	1.124605	.77459	1.958297
.31622	1.220527	.80622	2.024049
.38729	1.307354	.83666	2.089074
.44721	1.388838	.86602	2.153444
.50000	1.466656	.89443	2.217225
.54772	1.541746	.92195	2.280468
.59161	1.614772	.94868	2.343220
.63245	1.685915	.97468	2.405517
.67082	1.755688	1.00000	2.467400
.70710	1.824239		

Equation (1) is basically Irwin's expression (ref. 2) for an elliptical crack embedded in an infinite solid, with correction factors F and M applied to account for the finite thickness of the specimens. Correction factor F is for the effect of the free front surface (flawed side) of the plate on growth of the crack through the thickness. It was determined by using the equation below proposed by Kobayashi and Moss (ref. 3).

$$F = 1.0 + 0.12\left(1 - \frac{A}{2B}\right)^2 \tag{3}$$

The correction factor M is a function of A/T and A/2B and accounts for the effect of the back surface on flaw growth through the thickness. The factor was determined by a linear interpolation between Kobayashi's solution for $A/2B = 0$ and Smith's solution for $A/2B = 0.5$. The use of the Kobayashi and Smith solutions for back-face correction factors is discussed in reference 4. The linear interpolation procedure used for determining M is shown in figure 16. More recent and less approximate solutions exist for the correction factor M, such as by Kobayashi and Moss (ref. 3). These solutions were not used because it was desired to keep the publication of fracture toughness values consistent with those of other programs at the JSC. Also, because most flaws were not more than approximately halfway through the thickness, the variation in stress intensity factor values by using more rigorous solutions for M would not have been significant.

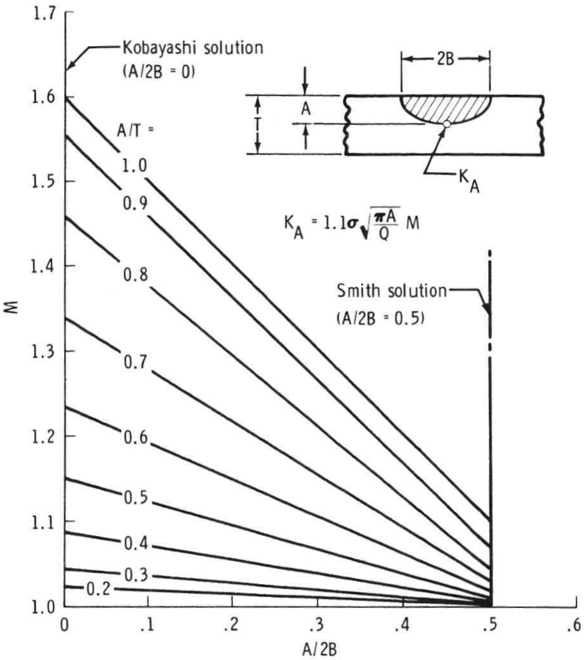


Figure 16.- Deep flaw magnification factor M used by the JSC.

To determine the fracture toughness values from the test data, equation (1) was written in the following form.

$$K_{IC} = F\sigma_c\sqrt{\frac{\pi A_f}{Q}}\,M \tag{4}$$

where, in determining Q for the above equation (from eq. (2)), the values of F_{TY} were assumed as follows.

As-welded specimens		Aged specimens	
RT	LN_2	RT	LN_2
145 MN/m^2 (21 ksi)	193 MN/m^2 (28 ksi)	207 MN/m^2 (30 ksi)	262 MN/m^2 (38 ksi)

The preceding values for the yield stress F_{TY} are the average values from those listed in table I for the EB welded specimens that were machined from the center section of the welds. The yield stress at this location does not differ significantly from the values at the center of either the pulse GTA or GMA welded specimens.

The fracture toughness test results were all obtained from the cross-weld specimens. These specimens were used to obtain both fracture toughness and fatigue crack growth rate data. The test results are listed in tables VII to X. A summary of the fracture toughness results for the three types of welds is presented in table VII. Listed in tables VIII to X are the detail data for each specimen tested. The fracture toughness values determined from the test data using equation (4) are listed in the tables as "apparent K_{IC}" because the failing stress σ_c, based on the gross cross-sectional area, approached or exceeded the yield stress in some tests. In addition, the flaw length 2B was sometimes too large, with respect to the specimen width ($2B/W \geq 0.20$), to give valid K_{IC} results.

The results of the fracture toughness tests indicate that, in all cases, the toughness of the welds was reduced considerably as a result of aging. Of the three types of welds, the pulse GTA had the least drop in toughness caused by postweld aging. A comparison of the three types of welds showed that, in the unaged condition, the fracture toughness of the GTA and EB welds was approximately the same and was higher than for the GMA welds; whereas, in the aged condition, the fracture toughness of the GTA welds was the highest. Also, although the GMA weld results were lower, the true toughness of GMA welds would not be as high as the average values listed because the GMA welded specimens had a pulse GTA weld root section that retarded the flaw growth. The retardation was actually observed in the examination on the fracture surfaces. For each of the three types of welds and the two aging conditions, the toughness values at room temperature and the values at LN_2 temperature were about the same.

TABLE VII. - SUMMARY OF APPARENT K_{IC} TEST RESULTS FOR 2219-T87 ALUMINUM WELD SPECIMENS

K_{IC} for EB welds, $MN/m^{3/2}$ $\left(ksi \sqrt{in.}\right)$				K_{IC} for GMA welds, $MN/m^{3/2}$ $\left(ksi \sqrt{in.}\right)$				K_{IC} for pulse GTA welds, $MN/m^{3/2}$ $\left(ksi \sqrt{in.}\right)$			
As welded		Aged		As welded		Aged		As welded		Aged	
RT air	LN_2	RT air	LN_2	RT air	LN_2	RT air	LN_2	RT air	LN_2	RT air	LN_2
51.9 (47.2)	59.0 (53.7)	32.3 (29.4)	37.9 (34.5)	39.1 (35.6)	40.7 (37.0)	36.3 (33.0)	30.9 (28.1)	48.8 (44.4)	54.1 (49.2)	40.0 (36.4)	55.0 (50.0)
52.6 (47.9)	60.3 (54.9)	37.4 (34.0)	38.2 (34.8)	44.3 (40.3)	42.1 (38.3)	30.3 (27.6)	35.3 (32.1)	55.8 (50.8)	55.0 (50.0)	45.5 (41.4)	42.9 (39.0)
50.8 (46.2)	73.4 (66.8)	32.3 (29.4)	45.5 (41.4)	39.7 (36.1)	49.2 (44.8)	36.9 (33.6)	34.5 (31.4)	59.1 (53.8)	53.3 (48.5)	44.9 (40.9)	41.0 (37.3)
56.7 (51.6)	63.2 (57.5)	33.3 (30.3)	37.8 (34.4)	39.2 (35.7)	53.4 (48.6)	36.3 (33.0)	34.9 (31.8)	57.4 (52.2)	61.0 (55.5)	47.9 (43.6)	41.5 (37.8)
59.9 (54.5)	53.4 (48.6)	31.5 (28.7)	39.1 (35.6)	44.0 (40.0)	50.4 (45.9)	35.2 (32.0)	36.6 (33.3)	--	56.0 (51.0)	--	--
57.9 (52.7)	53.3 (48.5)	34.3 (31.2)	36.6 (33.3)	45.1 (41.0)	43.2 (39.3)	31.3 (28.5)	--	--	54.7 (49.8)	--	--
49.7 (45.2)	55.0 (50.0)	--	--	45.5 (44.4)	48.7 (44.3)	--	--	--	--	--	--
52.6 (47.9)	56.8 (51.7)	--	--	44.0 (40.0)	42.9 (39.0)	--	--	--	--	--	--
72.2 (65.7)	--	--	--	--	--	--	--	--	--	--	--
56.4 (51.3)	--	--	--	--	--	--	--	--	--	--	--
52.5 (47.8)	--	--	--	--	--	--	--	--	--	--	--
[a]55.7 (50.7)	59.3 (54.0)	33.5 (30.5)	38.5 (35.0)	42.6 (38.8)	46.2 (42.1)	34.4 (31.3)	34.4 (31.3)	55.3 (50.3)	55.8 (50.8)	44.6 (40.6)	45.1 (41.0)

[a]Row lists computed average values.

TABLE VIII. - CRACK GROWTH TEST RESULTS FOR EB WELDED 2219-T87 ALUMINUM ALLOY

(a) SI units

Specimen number	Test environ-ment	T, cm	W, cm	$\Delta\sigma$, MN/m^2	R	N, cycles	Cyclic frequency, Hz	σ_c, MN/m^2	A_i, cm	$2B_i$, cm	A_f, cm	$2B_f$, cm	$\frac{A_f-A_i}{N}$, nm/cycle	$\Delta K_{avg.}$, MN/m$^{3/2}$	Apparent K_{IC}, MN/m$^{3/2}$
EB1-1[a]	Air, 294° K	5.232	22.924	--	--	--	--	207.67	--	--	1.600	6.299	--	--	51.9
EB1-A-1[a, b]	Air, 294° K	5.080	22.964	--	--	--	--	131.55	--	--	2.515	6.960	--	--	32.3
EB1-A-2	Air, 294° K	5.095	22.931	--	--	--	--	154.17	--	--	2.510	6.629	--	--	37.4
EB2-2A	Air, 294° K	5.034 -- --	22.901 -- --	65.98 131.97 65.98	0.05 .05 .05	500 5 800	0.5 .1 1	-- -- 134.24	2.535 2.659 3.861	6.401 6.462 6.538	2.659 3.860 --	6.462 6.538 6.574	2 489 2 402 840 --	16.9 34.3 --	-- -- --
EB2-3A	LN_2	5.080 -- --	22.934 -- --	43.51 130.59 65.29	0.05 .05 .05	2500 2 800	1.5 .1 1	-- -- 152.72	2.540 2.563 2.593	7.036 7.041 7.061	2.563 2.593 2.601	7.041 7.061 7.066	102 152 400 102	10.6 32.1 15.9	-- -- 37.8
EB3-1	LN_2	5.090	22.962	--	--	--	--	209.32	--	--	2.941	8.331	--	--	59.0
EB3-2[a]	Air, 294° K	5.093	22.936	--	--	--	--	190.43	--	--	2.769	8.153	--	--	52.6
EB3-3	Air, 294° K	4.597 -- --	22.916 -- --	63.29 202.71 168.92	0.5 0 0	500 1 20	0.5 .1 .1	-- -- 240.63	2.743 2.931 2.969	6.934 7.061 7.087	2.931 2.969 3.150	7.061 7.087 7.264	3 759 381 000 90 170	15.8 56.9 46.1	-- -- 72.2
EB4-1	Air, 294° K	5.083	22.936	--	--	--	--	192.71	--	--	2.946	7.442	--	--	50.8
EB4-2	Air, 294° K	5.090 --	22.962 --	65.09 128.66	0.050 .061	2500 17	1 .5	-- --	2.845 4.572	7.772 9.449	4.572 5.090	9.449 --	-- --	18.6 --	-- --
EB4-3A	LN_2	5.057 -- --	22.898 -- --	87.56 131.00 87.56	0.05 .05 .05	100 5 100	1 .1 1	-- -- 153.62	2.616 2.649 2.741	6.807 6.868 6.888	2.649 2.741 2.779	6.868 6.888 6.899	3 302 182 880 3 810	21.1 32.0 21.3	-- -- 37.9
EB5-1A	Air, 294° K	5.080 -- --	22.885 -- --	43.16 100.66 64.74	0.05 .05 .05	5000 50 500	1 .01 1	-- -- 129.21	2.616 2.870 3.305	6.833 6.858 6.970	2.870 3.053 3.114	6.858 6.970 6.990	508 35 560 1 219	10.4 24.8 15.9	-- -- 32.3

[a]Flaw put in weld root; undesignated specimens had flaw in weld face.

[b]"A" in specimen number signifies that specimen was postweld aged at 436° K for 24 hours.

TABLE VIII. - CRACK GROWTH TEST RESULTS FOR EB WELDED 2219-T87 ALUMINUM ALLOY - Continued

(a) SI units - Continued

Specimen number	Test environment	T, cm	W, cm	$\Delta\sigma$, MN/m^2	R	N, cycles	Cyclic frequency, Hz	σ_c, MN/m^2	A_i, cm	$2B_i$, cm	A_f, cm	$2B_f$, cm	$\frac{A_f - A_i}{N}$, nm/cycle	$\Delta K_{avg.}$, $MN/m^{3/2}$	Apparent K_{IC}, $MN/m^{3/2}$
EB5-2	Air, 294° K	5.080	22.911	65.36	0.05	700	0.5	--	2.819	7.544	3.175	7.686	5 080	17.0	--
		--	--	130.31	.05	1	.1	--	3.175	7.686	3.198	7.701	228 600	35.4	--
		--	--	65.36	.05	700	.5	194.91	3.198	7.701	3.327	7.767	1 854	17.3	56.7
EB5-3	LN_2	4.826	23.089	68.26	0.05	700	1	--	2.654	7.239	2.916	7.305	3 734	17.3	--
		--	--	136.52	.05	5	.1	--	2.916	7.305	2.977	7.371	121 920	35.6	--
		--	--	68.26	.05	700	1	219.60	2.977	7.371	2.990	7.381	178	17.6	60.3
EB6-1	Air, 294° K	5.182	22.962	--	--	--	--	216.08	--	--	2.891	7.798	--	--	57.9
EB6-2[a]	Air, 294° K	5.080	22.898	43.57	0.05	5 000	1	--	2.812	7.976	3.233	8.077	838	11.8	--
		--	--	101.70	.05	50	.1	--	3.233	8.077	3.401	8.214	33 528	28.2	--
		--	--	65.36	.05	500	1	196.91	3.401	8.214	3.447	8.255	914	18.0	59.9
EB6-3	LN_2	5.080	23.040	101.08	0.05	100	0.5	--	2.771	7.341	2.901	7.437	12 954	25.8	--
		--	--	158.58	.05	4	.1	--	2.901	7.437	2.946	7.483	114 300	41.6	--
		--	--	101.08	.05	100	.5	258.42	2.946	7.483	2.990	7.508	4 318	26.2	73.4
EB7-1A[a, b]	LN_2	5.085	22.924	--	--	--	--	137.34	--	--	2.921	8.636	--	--	38.2
EB7-2[a]	LN_2	5.105	22.888	101.35	0.048	400	0.5	--	3.023	8.890	4.064	9.830	25 400	30.6	--
		--	--	144.79	.050	5	.1	--	4.064	9.830	4.153	10.008	177 800	46.3	--
		--	--	101.35	.048	?	1	--	4.153	10.008	5.105	--	--	--	--
EB7-3A	LN_2	5.080	23.025	65.02	0.05	500	0.5	--	2.624	6.579	2.700	6.609	1 524	15.4	--
		--	--	108.39	.05	5	.1	--	2.700	6.609	2.715	6.624	30 480	25.8	--
		--	--	65.02	.05	700	1	187.12	2.715	6.624	2.738	6.629	330 200	15.4	45.4
EB8-1A	Air, 294° K	4.994	22.906	88.25	0.05	200	0.05	130.24	2.515	7.112	2.972	7.214	22 860	22.0	33.3
EB8-2	LN_2	5.029	22.974	44.33	0.05	5 000	1.5	229.46	2.718	7.468	2.769	7.483	102	11.2	63.2
EB8-3	LN_2	5.083	22.924	86.87	0.05	200	0.05	198.16	2.692	7.366	2.875	7.452	9 144	22.1	53.4
EB9-1A	Air, 294° K	5.085	22.911	34.34	0.50	2 365	1	--	2.540	6.553	2.616	6.604	330	8.0	--
		--	--	115.83	.05	1	.10	--	2.616	6.604	2.652	6.629	355 600	27.7	--
		--	--	34.34	.50	11 125	1	129.62	2.652	6.629	2.754	6.726	102	8.1	31.5

[a]Flaw put in weld root; undesignated specimens had flaw in weld face.

[b]"A" in specimen number signifies specimen was postweld aged at 436° K for 24 hours.

TABLE VIII. - CRACK GROWTH TEST RESULTS FOR EB WELDED 2219-T87 ALUMINUM ALLOY - Continued

(a) SI units - Concluded

Specimen number	Test environment	T, cm	W, cm	$\Delta\sigma$, MN/m^2	R	N, cycles	Cyclic frequency, Hz	σ_c, MN/m^2	A_i, cm	$2B_i$, cm	A_f, cm	$2B_f$, cm	$\frac{A_f-A_i}{N}$, nm/cycle	$\Delta K_{avg.}$, $MN/m^{3/2}$	Apparent K_{IC}, $MN/m^{3/2}$
EB9-2	Air, 294° K	5.100	22.901	34.27	0.50	5 226	1	--	2.896	7.595	3.185	7.671	559	8.8	--
		--	--	173.75	.05	1	.1	--	3.185	7.671	3.315	7.798	1 295 400	48.6	--
		--	--	65.09	.05	2 524	1	175.13	3.315	7.798	3.404	7.823	356	17.3	49.7
EB9-3	LN_2	5.088	22.901	72.39	0.05	300	0.5	--	2.764	7.442	2.921	7.498	5 258	18.5	--
		--	--	181.33	.05	1	.1	--	2.921	7.498	2.977	7.544	558 800	48.5	--
		--	--	72.39	.05	2 000	1	195.47	2.977	7.544	3.053	7.579	381	18.7	53.3
EB10-1A[b]	Air, 294° K	5.067	22.916	72.39	0.05	200	0.5	--	2.591	7.061	2.713	7.107	6 096	17.8	--
		--	--	116.52	.05	1	.1	--	2.713	7.107	2.730	7.122	177 800	29.1	--
		--	--	57.92	.05	500	1	135.96	2.730	7.122	2.733	7.127	51	14.3	34.3
EB10-2	Air, 294° K	5.037	22.995	87.56	0.05	200	0.5	--	2.667	7.569	2.819	7.701	7 620	22.7	--
		--	--	175.13	.05	1	.1	--	2.819	7.701	2.883	7.772	635 000	49.0	--
		--	--	87.56	.05	200	.5	182.71	2.883	7.772	2.934	7.838	2 540	23.2	52.6
EB10-3	LN_2	5.080	22.924	57.23	0.5	500	0.5	195.57	2.921	7.696	3.063	7.762	2 845	14.9	55.0
EB11-1A	LN_2	5.080	22.901	72.39	0.05	200	0.5	--	2.705	7.087	2.870	7.127	6 985	17.9	--
		--	--	123.42	.05	2	.1	--	2.845	7.127	2.888	7.142	215 900	30.9	--
		--	--	72.39	.05	2 000	1	154.10	2.888	7.142	3.683	7.341	3 962	18.2	39.1
EB11-2	Air, 294° K	5.057	22.916	38.40	0.5	2 000	1.5	--	2.311	6.934	2.375	6.980	305	9.1	--
		--	--	76.53	.5	200	1	--	2.375	6.980	2.545	7.010	8 509	18.5	--
		--	--	38.40	.5	2 000	1.5	203.40	2.545	7.010	2.591	7.137	229	9.3	56.4
EB11-3	Air, 294° K	5.080	22.911	30.54	0.50	6 000	1.5	--	2.718	7.264	2.845	7.346	203	7.6	--
		--	--	61.16	.50	2 000	1.0	--	2.845	7.346	3.962	9.195	5 588	16.8	--
		--	--	30.54	.50	10 000	1.5	152.86	3.962	9.195	3.973	9.195	10	9.0	55.5
EB12-1[a]	Air, 294° K	5.083	22.916	95.84	0.05	200	0.5	--	2.921	8.255	3.556	8.255	31 750	26.7	--
		--	--	162.72	.05	3	.1	170.99 (cyclic)	3.556	8.255	--	--	--	--	--
EB12-2A	LN_2	5.090	22.903	57.98	0.05	500	0.5	--	2.609	6.858	2.682	6.863	1 473	14.0	--
		--	--	101.49	.05	50	.5	--	2.682	6.863	2.863	6.914	36 068	24.7	--
		--	--	57.98	.05	500	.5	148.03	2.863	6.914	2.926	6.919	1 270	14.2	36.6
EB12-3	LN_2	5.057	22.967	58.19	0.05	500	1	--	2.695	7.722	2.741	7.757	914	14.9	--
		--	--	167.34	.05	3	.1	--	2.741	7.757	2.797	7.772	183 420	44.8	--
		--	--	87.29	.05	300	1	204.91	2.797	7.772	2.822	7.798	838	22.7	56.8

[a]Flaw put in weld root; undesignated specimens had flaw in weld face.

[b]"A" in specimen number signifies specimen was postweld aged at 436° K for 24 hours.

TABLE VIII. - CRACK GROWTH TEST RESULTS FOR EB WELDED 2219-T87 ALUMINUM ALLOY - Continued

(b) U.S. customary units

Specimen number	Test environment	T, in.	W, in.	$\Delta\sigma$, ksi	R	N, cycles	Cyclic frequency, Hz	σ_c, ksi	A_i, in.	$2B_i$, in.	A_f, in.	$2B_f$, in.	$\frac{A_f - A_i}{N}$, μin/cycle	$\Delta K_{avg.}$, ksi $\sqrt{in.}$	Apparent K_{IC}, ksi $\sqrt{in.}$
EB1-1[a]	Air, 70° F	2.060	9.025	--	--	--	--	30.12	--	--	0.630	2.48	--	--	47.2
EB1-A-1[a, b]	Air, 70° F	2.000	9.041	--	--	--	--	19.08	--	--	0.990	2.74	--	--	29.4
EB1-A-2	Air, 70° F	2.006	9.028	--	--	--	--	22.36	--	--	0.988	2.61	--	--	34.0
EB2-2A	Air, 70° F	1.982	9.016	9.57	0.05	500	0.5	--	0.998	2.520	1.047	2.544	98	15.4	--
		--	--	19.14	.05	5	.1	--	1.047	2.544	1.520	2.574	94 600	31.2	--
		--	--	9.57	.05	800	1	19.47	1.520	2.574	--	2.588	--	--	--
EB2-3A	LN_2	2.000	9.029	6.31	0.05	2 500	1.5	--	1.000	2.770	1.009	2.772	4	9.6	--
		--	--	18.94	.05	2	.1	--	1.009	2.772	1.021	2.780	6 000	29.2	--
		--	--	9.47	.05	800	1	22.15	1.021	2.780	1.024	2.782	4	14.5	34.4
EB3-1	LN_2	2.004	9.040	--	--	--	--	30.36	--	--	1.158	3.28	--	--	53.7
EB3-2[a]	Air, 70° F	2.005	9.030	--	--	--	--	27.62	--	--	1.090	3.21	--	--	47.9
EB3-3	Air, 70° F	1.810	9.022	9.18	0.5	500	0.5	--	1.080	2.730	1.154	2.780	148	14.4	--
		--	--	29.4	0	1	.1	--	1.154	2.780	1.169	2.790	15 000	51.8	--
		--	--	24.5	0	20	.1	34.90	1.169	2.790	1.240	2.860	3 550	42.0	65.7
EB4-1	Air, 70° F	2.001	9.030	--	--	--	--	27.95	--	--	1.160	2.93	--	--	46.2
EB4-2	Air, 70° F	2.004	9.040	9.44	0.050	2 500	1	--	1.12	3.06	1.80	3.72	--	16.9	--
		--	--	18.66	.061	17	.5	--	1.80	3.72	2.004	--	--	--	--
EB4-3A	LN_2	1.991	9.015	12.7	0.05	100	1	--	1.030	2.680	1.043	2.704	130	19.2	--
		--	--	19.0	.05	5	.1	--	1.043	2.704	1.079	2.712	7 200	29.1	--
		--	--	12.7	.05	100	1	22.28	1.079	2.712	1.094	2.716	150	19.4	34.5
EB5-1A	Air, 70° F	2.000	9.010	6.26	0.05	5 000	1	--	1.030	2.690	1.130	2.700	20	9.5	--
		--	--	14.60	.05	50	.01	--	1.130	2.700	1.202	2.744	1 400	22.6	--
		--	--	9.39	.05	500	1	18.74	1.202	2.744	1.226	2.752	48	14.5	29.4

[a]Flaw put in weld root; undesignated specimens had flaw in weld face.

[b]"A" in specimen number signifies that specimen was postweld aged at 325° F for 24 hours.

TABLE VIII. - CRACK GROWTH TEST RESULTS FOR EB WELDED 2219-T87 ALUMINUM ALLOY - Continued

(b) U.S. customary units - Continued

Specimen number	Test environment	T, in.	W, in.	$\Delta\sigma$, ksi	R	N, cycles	Cyclic frequency, Hz	σ_c, ksi	A_i, in.	$2B_i$, in.	A_f, in.	$2B_f$, in.	$\frac{A_f-A_i}{N}$, μin/cycle	$\Delta K_{avg.}$, ksi $\sqrt{in.}$	Apparent K_{IC}, ksi $\sqrt{in.}$
EB5-2	Air, 70° F	2.000 -- --	9.020 -- --	9.48 18.9 9.48	0.05 .05 .05	700 1 700	0.5 .1 .5	-- -- 28.27	1.110 1.250 1.259	2.97 3.026 3.032	1.250 1.259 1.310	3.026 3.032 3.058	200 9 000 73	15.5 32.2 15.7	-- -- 51.6
EB5-3	LN_2	1.900 -- --	9.090 -- --	9.90 19.8 9.90	0.05 .05 .05	700 5 700	1 .1 1	-- -- 31.85	1.045 1.148 1.172	2.850 2.876 2.902	1.148 1.172 1.177	2.876 2.902 2.906	147 4 800 7	15.7 32.4 16.0	-- -- 54.9
EB6-1	Air, 70° F	2.040	9.040	--	--	--	--	31.34	--	--	1.138	3.07	--	--	52.7
EB6-2[a]	Air, 70° F	2.000 -- --	9.015 -- --	6.32 14.75 9.48	0.05 .05 .05	5 000 50 500	1 .1 1	-- -- 28.56	1.107 1.273 1.339	3.140 3.180 3.234	1.273 1.339 1.357	3.180 3.234 3.250	33 1 320 36	10.7 25.7 16.4	-- -- 54.5
EB6-3	LN_2	2.000 -- --	9.071 -- --	14.66 23.0 14.66	0.05 .05 .05	100 4 100	0.5 .1 .5	-- -- 37.48	1.091 1.142 1.160	2.890 2.928 2.946	1.142 1.160 1.177	2.928 2.946 2.956	510 4 500 170	23.5 37.9 23.8	-- -- 66.8
EB7-1A[a, b]	LN_2	2.002	9.025	--	--	--	--	19.92	--	--	1.150	3.40	--	--	34.8
EB7-2[a]	LN_2	2.010 -- --	9.011 -- --	14.7 21.0 14.7	0.048 .050 .048	400 5 ?	0.5 .1 1	-- -- --	1.190 1.600 1.635	3.500 3.870 3.940	1.600 1.635 2.010	3.870 3.940 --	1 000 7 000 --	27.8 42.1 --	-- -- --
EB7-3A	LN_2	2.000 -- --	9.065 -- --	9.43 15.72 9.43	0.05 .05 .05	500 5 700	0.5 .1 1	-- -- 27.14	1.033 1.063 1.069	2.590 2.602 2.608	1.063 1.069 1.078	2.602 2.608 2.610	60 1 200 13	14.0 23.5 14.0	-- -- 41.4
EB8-1A	Air, 70° F	1.966	9.018	12.8	0.05	200	0.05	18.89	0.990	2.800	1.170	2.840	900	20.0	30.3
EB8-2	LN_2	1.980	9.045	6.43	0.05	5 000	1.5	33.28	1.070	2.940	1.090	2.946	4	10.2	57.5
EB8-3	LN_2	2.001	9.025	12.6	0.05	200	0.05	28.74	1.060	2.900	1.132	2.934	360	20.1	48.6
EB9-1A	Air, 70° F	2.002 -- --	9.020 -- --	4.98 16.8 4.98	0.50 .05 .50	2 365 1 11 125	1 .10 1	-- -- 18.8	1.000 1.030 1.044	2.580 2.600 2.610	1.030 1.044 1.084	2.600 2.610 2.648	13 14 000 4	7.3 25.2 7.4	-- -- 28.7

[a]Flaw put in weld root; undesignated specimens had flaw in weld face.

[b]"A" in specimen number signifies that specimen was postweld aged at 325° F for 24 hours.

TABLE VIII. - CRACK GROWTH TEST RESULTS FOR EB WELDED 2219-T87 ALUMINUM ALLOY - Concluded

(b) U.S. customary units - Concluded

Specimen number	Test environment	T, in.	W, in.	$\Delta\sigma$, ksi	R	N, cycles	Cyclic frequency, Hz	σ_c, ksi	A_i, in.	$2B_i$, in.	A_f, in.	$2B_f$, in.	$\frac{A_f-A_i}{N}$, μin/cycle	$\Delta K_{avg.}$, ksi $\sqrt{in.}$	Apparent K_{IC}, ksi $\sqrt{in.}$
EB9-2	Air, 70° F	2.008 -- --	9.016 -- --	4.97 25.2 9.44	0.50 .05 .05	5 226 1 2 524	1 .1 1	-- -- 25.4	1.140 1.254 1.305	2.990 3.020 3.070	1.254 1.305 1.340	3.020 3.070 3.080	22 51 000 14	8.0 44.2 15.7	-- -- 45.2
EB9-3	LN_2	2.003 -- --	9.016 -- --	10.5 26.3 10.5	0.05 .05 .05	300 1 2 000	0.5 .1 1	-- -- 28.35	1.088 1.150 1.172	2.930 2.952 2.970	1.150 1.172 1.202	2.952 2.970 2.984	207 22 000 15	16.8 44.1 17.0	-- -- 48.5
EB10-1A[b]	Air, 70° F	1.995 -- --	9.022 -- --	10.5 16.9 8.4	0.05 .05 .05	200 1 500	0.5 .1 1	-- -- 19.72	1.020 1.068 1.075	2.780 2.798 2.804	1.068 1.075 1.076	2.798 2.804 2.806	240 7 000 2	16.2 26.5 13.0	-- -- 31.2
EB10-2	Air, 70° F	1.983 -- --	9.053 -- --	12.7 25.4 12.7	0.05 .05 .05	200 1 200	0.5 .1 .5	-- -- 26.5	1.050 1.110 1.135	2.980 3.032 3.060	1.110 1.135 1.155	3.032 3.060 3.086	300 25 000 100	20.7 44.6 21.1	-- -- 47.9
EB10-3	LN_2	2.000	9.025	8.3	0.5	500	0.5	28.8	1.150	3.030	1.206	3.056	112	13.6	50.1
EB11-1A	LN_2	2.000 -- --	9.016 -- --	10.5 17.9 10.5	0.05 .05 .05	200 2 2 000	0.5 .1 1	-- -- 22.35	1.065 1.120 1.137	2.790 2.806 2.812	1.130 1.137 1.450	2.806 2.812 2.890	275 8 500 156	16.3 28.1 16.6	-- -- 35.6
EB11-2	Air, 70° F	1.991 -- --	9.022 -- --	5.57 11.1 5.57	0.5 .5 .5	2 000 200 2 000	1.5 1 1.5	-- -- 29.5	0.910 .935 1.002	2.730 2.748 2.760	0.935 1.002 1.020	2.748 2.760 2.810	12 335 9	8.3 16.8 8.5	-- -- 51.3
EB11-3	Air, 70° F	-- 2.000 --	9.020 -- --	4.43 8.87 4.43	0.50 .50 .50	6 000 2 000 10 000	1.5 1.0 1.5	-- -- 22.17	1.070 1.120 1.560	2.860 2.892 3.620	1.120 1.560 1.564	2.892 3.620 3.620	8 220 .4	6.9 15.3 8.2	-- -- 47.8
EB12-1[a]	Air, 70° F	2.001 --	9.022 --	13.9 23.6	0.05 .05	200 3	0.5 .1	-- 24.8 (cyclic)	1.150 1.400	3.250 3.250	1.400 --	3.250 --	1 250 --	24.3 --	-- --
EB12-2A	LN_2	2.004 -- --	9.017 -- --	8.41 14.72 8.41	0.05 .05 .05	500 50 500	0.5 .5 .5	-- -- 21.47	1.027 1.056 1.127	2.700 2.702 2.722	1.056 1.127 1.152	2.702 2.722 2.724	58 1 420 50	12.7 22.5 12.9	-- -- 33.3
EB12-3	LN_2	1.991 -- --	9.042 -- --	8.44 24.27 12.66	0.05 .05 .05	500 3 300	1 .1 1	-- -- 29.72	1.061 1.079 1.101	3.040 3.054 3.060	1.079 1.101 1.111	3.054 3.060 3.070	36 7 300 33	13.6 40.8 20.7	-- -- 51.7

[a]Flaw put in weld root; undesignated specimens had flaw in weld face.

[b]"A" in specimen number signifies specimen was postweld aged at 325° F for 24 hours.

TABLE IX. - CRACK GROWTH TEST RESULTS FOR GMA WELDED 2219-T87 ALUMINUM ALLOY

(a) SI units

Specimen number	Test environment	T, cm	W, cm	$\Delta\sigma$, MN/m^2	R	N, cycles	Cyclic frequency, Hz	σ_c, MN/m^2	A_i, cm	$2B_i$, cm	A_f, cm	$2B_f$, cm	$\frac{A_f-A_i}{N}$, nm/cycle	$\Delta K_{avg.}$, $MN/m^{3/2}$	Apparent K_{IC}, $MN/m^{3/2}$
MG1-1	Air, 294° K	5.080	22.929	--	--	--	--	162.0	2.009	6.325	--	--	--	--	39.1
MG1-2	LN_2	5.080	22.896	65.397	0.05	1 500	1	168.2	2.045	6.670	2.184	6.680	940	15.1	40.7
MG1-3A[a]	Air, 294° K	5.047 -- --	22.995 -- --	58.261 102.042 58.261	0.05 .05 .05	2 000 100 2 000	1 1 1	-- -- 139.9	1.930 2.108 2.261	6.604 6.655 8.204	2.108 2.261 2.286	6.655 8.204 8.217	889 15 240 127	13.2 24.8 14.7	-- -- 36.3
MG2-1A	LN_2	5.080	22.911	65.362	0.05	2 000	1	129.0	1.890	7.112	2.070	7.468	889	15.3	30.9
MG2-2A	Air, 294° K	5.034 -- --	22.890 -- --	43.989 109.627 43.989	0.05 .05 .05	10 000 5 10 000	1.5 .1 1.5	-- -- 129.6	1.956 2.235 2.413	6.858 7.366 10.414	2.245 2.413 2.428	7.366 10.414 10.444	279 355 600 25	10.3 29.0 12.2	-- -- 36.9
MG2-3	Air, 294° K	5.080	22.911	98.043	0.05	450	0.5	173.7	1.905	6.274	2.134	6.782	5 080	22.6	44.3
MG3-1A	Air, 294° K	5.090	22.911	65.224	0.05	2 000	1	129.6	1.821	6.223	2.032	6.731	1 054	14.5	30.3
MG3-2	Air, 294° K	5.055	22.911	65.679	0.05	1 000	0.5	161.3	1.994	6.274	2.134	6.477	1 397	14.8	39.7
MG3-3	Air, 294° K	5.085 -- --	23.012 -- --	86.667 129.966 86.667	0.05 .05 .05	600 10 600	0.5 .1 .5	-- -- 155.1	1.941 2.200 2.469	5.918 6.299 6.731	2.200 2.469 2.517	6.299 6.731 6.736	4 318 269 240 805	19.4 31.3 20.9	-- -- 39.2
MG4-1	LN_2	5.105 -- --	22.890 -- --	86.736 130.173 86.736	0.05 .05 .05	600 10 1 000	1 .1 1	-- -- 171.3	1.880 2.111 2.172	6.579 6.782 6.834	2.111 2.172 2.217	6.782 6.833 6.858	3 861 60 960 457	19.8 30.9 20.4	-- -- 42.1
MG4-2	LN_2	5.042 --	22.865 --	109.971 58.674	0.05 .05	100 2 000	0.5 1	-- 179.3	2.012 2.167	6.756 7.087	2.167 2.169	7.087 7.087	15 494 13	25.9 13.8	-- 49.2
MG4-3	Air, 294° K	5.057 --	22.860 --	109.627 58.468	0.05 .05	132 2 000	0.5 1	-- 164.3	1.994 2.281	6.680 7.544	2.281 2.306	7.544 7.544	21 742 127	26.7 14.4	-- 44.0

[a]"A" in specimen number signifies specimen was postweld aged at 436° K for 24 hours.

TABLE IX. - CRACK GROWTH TEST RESULTS FOR GMA WELDED 2219-T87 ALUMINUM ALLOY - Continued

(a) SI units - Concluded

Specimen number	Test environment	T, cm	W, cm	$\Delta\sigma$, MN/m^2	R	N, cycles	Cyclic frequency, Hz	σ_c', MN/m^2	A_i', cm	$2B_i$', cm	A_f', cm	$2B_f$', cm	$\frac{A_f-A_i}{N}$, nm/cycle	$\Delta K_{avg.}$', MN/m$^{3/2}$	Apparent K_{IC}', MN/m$^{3/2}$
MG5-1A[a]	Air, 294° K	5.105	22.890	58.47	0.05	2 000	1	--	1.753	6.655	2.057	7.747	1 524	13.4	--
		--	--	116.94	.05	1	.1	--	2.057	7.747	2.362	11.684	3 048 000	31.3	--
		--	--	58.47	.05	4 000	1	121.97	2.362	11.684	2.515	11.684	381	16.7	36.3
MG5-2A	LN_2	5.080	22.865	87.29	0.05	500	0.5	134.03	2.032	6.934	2.497	8.331	9 296	21.4	35.3
MG5-3A	LN_2	5.042	23.025	114.94	0	1	0.1	--	1.862	6.680	2.012	7.874	1 498 600	76.9	--
		--	--	58.26	.05	2 500	1	128.24	2.012	7.874	2.057	7.874	178	14.1	34.5
MG8-1A	Air, 294° K	5.032	22.880	88.11	0.05	600	1	123.28	1.905	6.604	2.451	8.001	9 093	21.2	35.2
MG9-1A	Air, 294° K	5.047	22.880	--	--	--	--	124.11	--	--	1.875	6.782	--	--	31.3
MG9-2A	LN_2	5.072	22.911	126.31	0	1	0.1	--	1.897	6.579	2.451	7.112	5 537 200	29.8	--
		--	--	58.19	.05	3 000	1	129.76	2.451	7.112	2.459	7.127	25	14.1	34.9
MG9-3A	LN_2	5.037	23.000	72.95	0.05	1 500	1	--	1.857	6.706	1.976	7.264	787	16.7	--
		--	--	109.42	.05	1	.1	--	1.976	7.264	2.789	9.652	8 128 000	28.5	--
		--	--	72.95	.05	2 000	1	115.21	2.789	9.652	2.842	9.652	254	20.9	36.6
MG10-1	Air, 294° K	5.085	22.885	116.18	0.05	50	0.5	--	1.887	6.528	2.073	6.731	37 084	27.1	--
		--	--	72.60	.05	2 000	1	162.44	2.073	6.731	2.197	6.782	610	16.9	45.1
MG10-2	LN_2	5.108	22.865	57.92	0.05	2 000	1	--	1.781	6.706	1.875	6.756	457	13.0	--
		--	--	114.72	.05	1	.1	--	1.875	6.756	1.905	6.769	304 800	33.6	--
		--	--	72.39	.05	2 000	1	199.95	1.905	6.769	1.908	6.769	25	16.4	53.4
MG10-3	LN_2	5.093	22.911	160.10	0	1	0.1	--	1.869	6.680	1.915	6.706	457 200	37.6	--
		--	--	86.94	.05	1 000	1	189.88	1.915	6.706	1.958	6.718	432	19.8	50.4
MG11-1	LN_2	5.047	22.860	102.53	0.05	200	0.5	--	1.864	6.706	1.905	6.782	3 302	23.3	--
		--	--	58.61	.05	3 000	1	164.99	1.905	6.782	1.946	6.782	127	13.3	43.2
MG11-2	Air, 294° K	5.098	22.865	152.65	0	1	0.1	--	1.948	6.883	2.111	7.163	1 625 600	38.2	--
		--	--	72.53	.05	2 000	1	160.30	2.111	7.163	2.174	7.214	305	17.4	45.5
MG11-3	LN_2	22.888	5.085	72.60	0.05	1 500	1	--	1.875	6.934	1.994	7.010	787	16.7	--
		--	--	152.51	.05	1	.1	--	1.994	7.010	2.045	7.264	508 000	36.8	--
		--	--	72.60	.05	2 000	1	177.75	2.045	7.264	2.065	7.277	102	17.1	48.7
MG12-1	Air, 294° K	22.936	5.136	43.02	0.05	5 000	1.5	--	1.892	6.680	2.141	6.858	508	9.9	--
		--	--	129.14	.05	5	.1	--	2.141	6.858	2.189	6.985	96 520	31.5	--
		--	--	71.77	.05	1 500	1	156.72	2.189	6.985	2.240	7.010	330	17.1	44.0
MG12-2	LN_2	22.918	5.095	115.83	0.05	100	0.5	159.96	1.918	6.579	2.134	6.960	21 590	26.9	42.9

[a]"A" in specimen number signifies specimen was postweld aged at 436° K for 24 hours.

TABLE IX. - CRACK GROWTH TEST RESULTS FOR GMA WELDED 2219-T87 ALUMINUM ALLOY - Continued

(b) U.S. customary units

Specimen number	Test environment	T, in.	W, in.	$\Delta\sigma$, ksi	R	N, cycles	Cyclic frequency, Hz	σ_c, ksi	A_i, in.	$2B_i$, in.	A_f, in.	$2B_f$, in.	$\frac{A_f-A_i}{N}$, μin/cycle	$\Delta K_{avg.}$, ksi $\sqrt{in.}$	Apparent K_{IC}, ksi $\sqrt{in.}$
MG1-1	Air, 70° F	2.000	9.027	--	--	--	--	23.5	0.791	2.490	--	--	--	--	35.6
MG1-2	LN_2	2.000	9.014	9.485	0.05	1 500	1	24.4	0.805	2.626	0.860	2.630	37	13.7	37.0
MG1-3A[a]	Air, 70° F	1.987 -- --	9.053 -- --	8.45 14.8 8.45	0.05 .05 .05	2 000 100 2 000	1 1 1	-- -- 20.29	0.760 .830 .890	2.600 2.620 3.23	0.830 .890 .900	2.620 3.230 3.235	35 600 5	12.0 22.6 13.4	-- -- 33.0
MG2-1A	LN_2	2.000	9.020	9.48	0.05	2 000	1	18.57	0.744	2.800	0.815	2.940	35	13.9	28.1
MG2-2A	Air, 70° F	1.982 -- --	9.012 -- --	6.38 15.9 6.38	0.05 .05 .05	10 000 5 10 000	1.5 .1 1.5	-- -- 18.8	0.770 .880 .950	2.700 2.900 4.100	0.880 .950 .956	2.900 4.100 4.112	11 14 000 1	9.4 26.4 11.1	-- -- 33.6
MG2-3	Air, 70° F	2.000	9.020	14.22	0.05	450	0.5	25.2	0.750	2.470	0.840	2.670	200	20.6	40.3
MG3-1A	Air, 70° F	2.004	9.020	9.46	0.05	2 000	1	18.8	0.717	2.450	0.800	2.650	41.5	13.2	27.6
MG3-2	Air, 70° F	1.990	9.020	9.526	0.05	1 000	0.5	23.4	0.785	2.470	0.840	2.550	55	13.5	36.1
MG3-3	Air, 70° F	2.002 -- --	9.060 -- --	12.57 18.85 12.57	0.05 .05 .05	600 10 600	0.5 .1 .5	-- -- 22.5	0.764 .866 .972	2.330 2.480 2.650	0.866 .972 .991	2.480 2.650 2.652	170 10 600 31.7	17.7 28.5 19.0	-- -- 35.7
MG4-1	LN_2	2.010 -- --	9.012 -- --	12.58 18.88 12.58	0.05 .05 .05	600 10 1 000	1 .1 1	-- -- 24.84	0.740 .831 .855	2.590 2.670 2.690	0.831 .855 .873	2.670 2.690 2.700	152 2 400 18	18.0 28.1 18.6	-- -- 38.3
MG4-2	LN_2	1.985 --	9.002 --	15.95 8.51	0.05 .05	100 2 000	0.5 1	-- 26.0	0.792 .853	2.660 2.790	0.853 .854	2.790 2.790	610 .5	23.6 12.6	-- 44.8
MG4-3	Air, 70° F	1.991 --	9.000 --	15.90 8.48	0.05 .05	132 2 000	0.5 1	-- 23.83	0.785 .898	2.630 2.970	0.898 .908	2.970 2.970	856 5	24.3 13.1	-- 40.0

[a]"A" in specimen number signifies specimen was postweld aged at 325° F for 24 hours.

TABLE IX. - CRACK GROWTH TEST RESULTS FOR GMA WELDED 2219-T87 ALUMINUM ALLOY - Concluded

(b) U.S. customary units - Concluded

Specimen number	Test environment	T, in.	W, in.	$\Delta\sigma$, ksi	R	N, cycles	Cyclic frequency, Hz	σ_c, ksi	A_i, in.	$2B_i$, in.	A_f, in.	$2B_f$, in.	$\frac{A_f - A_i}{N}$, μin/cycle	$\Delta K_{avg.}$, ksi $\sqrt{in.}$	Apparent K_{IC}, ksi $\sqrt{in.}$
MG5-1A[a]	Air, 70° F	2.010 -- --	9.012 -- --	8.48 16.96 8.48	0.05 .05 .05	2 000 1 4 000	1 .1 1	-- -- 17.69	0.690 .810 .930	2.620 3.050 4.600	0.810 .930 .990	3.050 4.600 4.600	60 120 000 15	12.2 28.5 15.2	-- -- 33.0
MG5-2A	LN_2	2.000	9.002	12.66	0.05	500	0.5	19.44	0.800	2.730	0.983	3.280	366	19.5	32.1
MG5-3A	LN_2	1.985 --	9.065 --	16.67 8.45	0 .05	1 2 500	0.1 1	-- 18.6	0.733 .792	2.630 3.100	0.792 .810	3.100 3.100	59 000 7	24.5 12.8	-- 31.4
MG8-1A	Air, 70° F	1.981	9.008	12.78	0.05	600	1	17.88	0.750	2.600	0.965	3.150	358	19.3	32.0
MG9-1A	Air, 70° F	1.987	9.008	--	--	--	--	18.0	--	--	0.738	2.670	--	--	28.5
MG9-2A	LN_2	1.997 --	9.020 --	18.32 8.44	0 .05	1 3 000	0.1 1	-- 18.82	0.747 .965	2.590 2.800	0.965 .968	2.800 2.806	218 000 1	27.1 12.8	-- 31.8
MG9-3A	LN_2	1.983 -- --	9.055 -- --	10.58 15.87 10.58	0.05 .05 .05	1 500 1 2 000	1 .1 1	-- -- 16.71	0.731 .778 1.098	2.640 2.860 3.800	0.778 1.098 1.119	2.860 3.800 3.800	31 320 000 10	15.2 25.9 19.0	-- -- 33.3
MG10-1	Air, 70° F	2.002 --	9.010 --	16.85 10.53	0.05 .05	50 2 000	0.5 1	-- 23.56	0.743 .816	2.570 2.650	0.816 .865	2.650 2.670	1 460 24	24.7 15.4	-- 41.0
MG10-2	LN_2	2.011 -- --	9.002 -- --	8.40 20.99 10.50	0.05 .05 .05	2 000 1 2 000	1 .1 1	-- -- 29.00	0.701 .738 .750	2.640 2.660 2.665	0.738 .750 .751	2.660 2.665 2.665	18 12 000 1	11.8 30.6 14.9	-- -- 48.6
MG10-3	LN_2	2.005 --	9.020 --	23.22 12.61	0 .05	1 1 000	0.1 1	-- 27.54	0.736 .754	2.630 2.640	0.754 .771	2.640 2.645	18 000 17	34.2 18.0	-- 45.9
MG11-1	LN_2	1.987 --	9.000 --	14.87 8.50	0.05 .05	200 3 000	0.5 1	-- 23.93	0.734 .750	2.640 2.670	0.750 .766	2.670 2.670	130 5	21.2 12.1	-- 39.3
MG11-2	Air, 70° F	2.007 --	9.002 --	22.14 10.52	0 .05	1 2 000	0.1 1	-- 23.25	0.767 .831	2.710 2.820	0.831 .856	2.820 2.840	64 000 12	34.8 15.8	-- 41.4
MG11-3	LN_2	9.011 -- --	2.002 -- --	10.53 22.12 10.53	0.05 .05 .05	1 500 1 2 000	1 .1 1	-- -- 25.78	0.738 .785 .805	2.730 2.760 2.860	0.785 .805 .813	2.760 2.860 2.865	31 20 000 4	15.2 33.5 15.6	-- -- 44.3
MG12-1	Air, 70° F	9.030 -- --	2.022 -- --	6.24 18.73 10.41	0.05 .05 .05	5 000 5 1 500	1.5 .1 1	-- -- 22.73	0.745 .843 .862	2.630 2.700 2.750	0.843 .862 .882	2.700 2.750 2.760	20 3 800 13	9.0 28.7 15.6	-- -- 40.0
MG12-2	LN_2	9.023	2.006	16.80	0.05	100	0.5	23.20	0.755	2.590	0.840	2.740	850	24.5	39.0

[a]"A" in specimen number signifies specimen was postweld aged at 325° F for 24 hours.

TABLE X. - CRACK GROWTH TEST RESULTS FOR PULSE GTA WELDED 2219-T87 ALUMINUM ALLOY

(a) SI units

Specimen number	Test environment	T, cm	W, cm	$\Delta\sigma$, MN/m^2	R	N, cycles	Cyclic frequency, Hz	σ_c, MN/m^2	A_i, cm	$2B_i$, cm	A_f, cm	$2B_f$, cm	$\frac{A_f-A_i}{N}$, nm/cycle	$\Delta K_{avg.}$, $MN/m^{3/2}$	Apparent K_{IC}, $MN/m^{3/2}$
PT1-1	Air, 294° K	5.083	22.901	65.36	0.05	2 500	1	187.26	1.920	6.452	2.177	6.833	1 016	15.0	48.8
PT1-2A[a]	Air, 294° K	5.075	22.898	65.43	0.05	2 000	1	174.58	1.572	6.071	1.864	6.299	1 448	14.0	40.0
PT1-3	Air, 294° K	5.083 -- --	22.962 -- --	43.44 130.31 43.44	0.05 .05 .05	15 000 15 15 000	1 .1 1	-- -- 205.46	1.618 1.966 2.042	6.604 6.858 7.112	1.966 2.042 2.047	6.858 7.112 7.112	229 50 800 2	9.7 31.6 10.1	-- -- 55.8
PT2-1	LN_2	5.080	22.924	65.29	0.05	2 500	1	212.01	2.009	6.807	2.225	6.970	864	15.3	54.1
PT2-2	Air, 294° K	-- 5.067 --	-- 22.875 --	43.71 145.48 43.71	0.05 .05 .05	10 000 5 15 000	1.5 .1 1.5	-- -- 203.40	1.842 2.083 2.121	6.706 6.858 6.909	2.083 2.121 2.258	6.858 6.909 6.909	229 76 200 102	10.0 35.8 10.2	-- -- 54.9
PT2-3	LN_2	5.080 -- --	23.012 -- --	72.26 144.58 72.26	0.05 .05 .05	2 000 5 2 500	1 .1 1	-- -- 213.05	1.994 2.225 2.261	6.756 6.975 7.041	2.225 2.261 2.294	6.975 7.041 7.046	1 143 71 120 127	16.8 35.3 17.3	-- -- 54.9
PT3-1A	Air, 294° K	5.123	22.903	86.46	0.05	2 064	1	194.33	1.372	6.502	1.676	7.010	1 473	18.5	45.5
PT3-2A	LN_2	5.070	22.888	66.43	0.05	2 000	1	187.47	1.572	6.604	1.775	6.706	1 016	14.2	42.9
PT3-3A	LN_2	5.080 -- --	23.076 -- --	57.64 144.17 57.64	0.05 .05 .05	2 500 5 2 500	1 .1 1	-- -- 176.44	1.359 1.480 1.758	6.706 6.756 7.188	1.481 1.758 1.760	6.756 7.188 7.188	483 553 720 25	12.0 32.0 13.0	-- -- 41.0
PT4-1	LN_2	5.080 -- --	22.901 -- --	87.15 145.27 87.15	0.05 .05 .05	1 000 5 1 000	1 .1 1	-- -- 208.36	1.862 2.111 2.182	6.680 6.934 7.036	2.111 2.182 2.217	6.934 7.036 7.087	2 489 142 240 356	20.0 35.1 20.8	-- -- 53.3
PT4-2	LN_2	5.072 -- --	22.870 -- --	58.26 109.28 58.26	0.05 .05 .05	2 500 50 3 000	1 .5 1	-- -- 222.42	1.816 1.859 1.900	6.655 6.695 6.746	1.859 1.900 1.913	6.695 6.746 6.756	178 8 128 51	13.0 24.9 13.2	-- -- 60.7
PT4-3	Air, 294° K	5.080	22.974	86.87	0.05	1 045	1	196.29	1.816	6.985	2.139	7.391	3 073	20.5	59.1

[a]"A" in specimen number signifies specimen was postweld aged at 436° K for 24 hours.

TABLE X. - CRACK GROWTH TEST RESULTS FOR PULSE GTA WELDED 2219-T87 ALUMINUM ALLOY - Continued

(a) SI units - Concluded

Specimen number	Test environment	T, cm	W, cm	$\Delta\sigma$, MN/m^2	R	N, cycles	Cyclic frequency, Hz	σ_c, MN/m^2	A_i, cm	$2B_i$, cm	A_f, cm	$2B_f$, cm	$\frac{A_f - A_i}{N}$, nm/cycle	$\Delta K_{avg.}$, $MN/m^{3/2}$	Apparent K_{IC}, $MN/m^{3/2}$
PT5-1A[a]	Air, 294° K	5.065	22.957	116.31	0.05	10	0.1	--	1.816	6.731	1.854	6.782	38 100	26.4	--
		--	--	58.12	.05	2 500	1	173.68	1.854	6.782	1.869	6.795	51	13.1	44.9
PT5-2A	Air, 294° K	5.080	22.936	167.96	0	1	0.1	--	1.562	6.553	2.007	9.652	4 445 000	41.2	--
		--	--	87.01	.05	2 500	1	161.48	2.007	9.652	2.108	9.677	406	22.4	47.9
PT5-3A	LN_2	5.029	23.050	116.66	0.05	10	0.1	--	1.633	6.604	1.740	6.706	106 680	25.6	--
		--	--	58.33	.05	2 500	1	166.92	1.740	6.706	1.753	6.706	51	12.9	41.5
PT6-1	Air, 294° K	5.062	22.860	109.49	0.05	200	0.5	--	1.679	6.477	1.913	6.934	11 684	25.1	--
		--	--	167.96	.05	1	.1	--	1.913	6.934	1.969	7.366	558 800	42.3	--
		--	--	87.63	.05	1 500	1	192.16	1.969	7.366	2.111	7.379	940	21.1	57.4
PT6-2	LN_2	5.060	22.888	109.49	0.05	200	0.5	--	1.788	6.680	2.062	7.010	13 716	25.3	--
		--	--	175.13	.05	2	.1	--	2.062	7.010	2.253	8.306	952 500	44.6	--
		--	--	87.56	.05	1 500	1	188.23	2.253	8.306	2.294	8.331	279	22.3	56.0
PT6-3	LN_2	5.121	22.936	129.55	0.05	10	0.1	--	1.773	6.706	1.859	6.756	86 360	29.6	--
		--	--	71.98	.05	2 500	1	204.50	1.859	6.756	1.885	6.769	102	16.3	54.7

[a]"A" in specimen number signifies specimen was postweld aged at 436° K for 24 hours.

TABLE X. - CRACK GROWTH TEST RESULTS FOR PULSE GTA WELDED 2219-T87 ALUMINUM ALLOY - Continued

(b) U.S. customary units

Specimen number	Test environment	T, in.	W, in.	$\Delta\sigma$, ksi	R	N, cycles	Cyclic frequency, Hz	σ_c, ksi	A_i, in.	$2B_i$, in.	A_f, in.	$2B_f$, in.	$\frac{A_f - A_i}{N}$, μin/cycle	$\Delta K_{avg.}$, ksi $\sqrt{in.}$	Apparent K_{IC}, ksi $\sqrt{in.}$
PT1-1	Air, 70° F	2.001	9.016	9.48	0.05	2 500	1	27.16	0.756	2.540	0.857	2.690	40	13.7	44.4
PT1-2A[a]	Air, 70° F	1.998	9.015	9.49	0.05	2 000	1	25.32	0.619	2.390	0.734	2.480	57	12.7	36.4
PT1-3	Air, 70° F	2.001 -- --	9.040 -- --	6.30 18.9 6.30	0.05 .05 .05	15 000 15 15 000	1 .1 1	-- -- 29.80	0.637 .774 .804	2.600 2.700 2.800	0.774 .804 .805	2.700 2.800 2.800	9 2 000 .07	8.8 28.7 9.2	-- -- 50.8
PT2-1	LN_2	2.000	9.025	9.47	0.05	2 500	1	30.75	0.791	2.680	0.876	2.744	34	13.9	49.2
PT2-2	Air, 70° F	-- 1.995 --	9.006 -- --	6.34 21.1 6.34	0.05 .05 .05	10 000 5 15 000	1.5 .1 1.5	-- -- 29.50	0.725 .820 .835	2.640 2.700 2.720	0.820 .835 .889	2.700 2.720 2.720	9 3 000 4	9.1 32.6 9.3	-- -- 50.0
PT2-3	LN_2	2.000 -- --	9.060 -- --	10.48 20.97 10.48	0.05 .05 .05	2 000 5 2 500	1 .1 1	-- -- 30.90	0.785 .876 .890	2.660 2.746 2.772	0.876 .890 .903	2.746 2.772 2.774	45 2 800 5	15.3 32.1 15.7	-- -- 50.0
PT3-1A	Air, 70° F	2.017	9.017	12.54	0.05	2 064	1	28.04	0.540	2.560	0.660	2.760	58	16.8	41.4
PT3-2A	LN_2	1.996	9.011	9.49	0.05	2 000	1	27.19	0.619	2.600	0.699	2.640	40	12.9	39.0
PT3-3A	LN_2	2.000 -- --	9.085 -- --	8.36 20.91 8.36	0.05 .05 .05	2 500 5 2 500	1 .1 1	-- -- 25.59	0.535 .583 .692	2.640 2.660 2.830	0.583 .692 .695	2.660 2.830 2.830	19 21 800 1	10.9 29.1 11.8	-- -- 37.3
PT4-1	LN_2	2.000 -- --	9.016 -- --	12.64 21.07 12.64	0.05 .05 .05	1 000 5 1 000	1 .1 1	-- -- 30.22	0.733 .831 .859	2.630 2.730 2.770	0.831 .859 .873	2.730 2.770 2.790	98 5 600 14	18.2 31.9 18.9	-- -- 48.5
PT4-2	LN_2	1.997 -- --	9.004 -- --	8.45 15.85 8.45	0.05 .05 .05	2 500 50 3 000	1 .5 1	-- -- 32.26	0.715 .732 .748	2.620 2.636 2.656	0.732 .748 .753	2.636 2.656 2.660	7 820 2	11.8 22.7 12.0	-- -- 55.2
PT4-3	Air, 70° F	2.000	9.045	12.60	0.05	1 045	1	28.47	0.715	2.750	0.842	2.910	121	18.7	53.8

[a]"A" in specimen number signifies specimen was postweld aged at 325° F for 24 hours.

TABLE X. - CRACK GROWTH TEST RESULTS FOR PULSE GTA WELDED 2219-T87 ALUMINUM ALLOY - Concluded

(b) U.S. customary units - Concluded

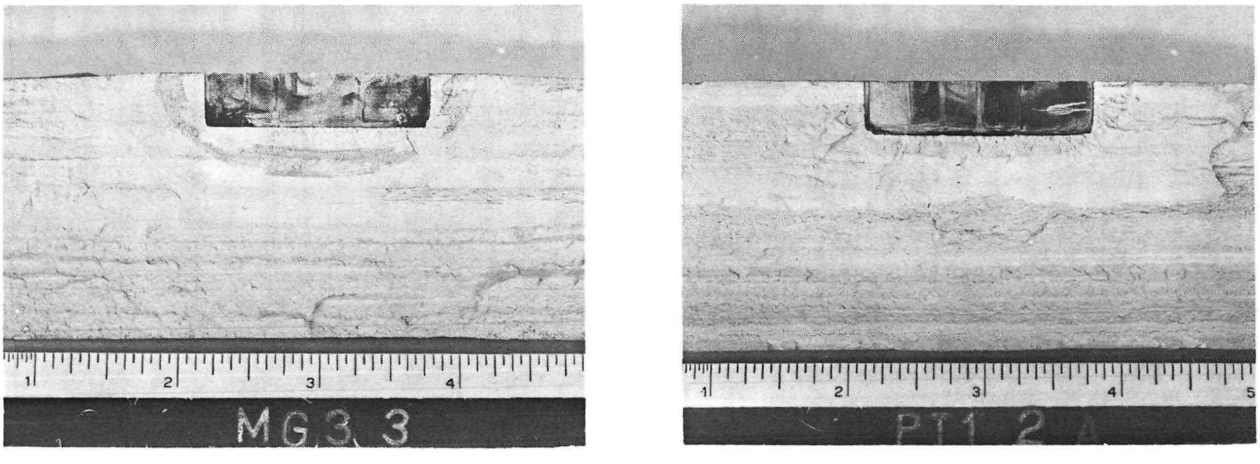
Specimen number	Test environment	T, in.	W, in.	$\Delta\sigma$, ksi	R	N, cycles	Cyclic frequency, Hz	σ_c, ksi	A_i, in.	$2B_i$, in.	A_f, in.	$2B_f$, in.	$\frac{A_f-A_i}{N}$, μin/cycle	$\Delta K_{avg.}$, ksi $\sqrt{in}$	Apparent K_{IC}, ksi $\sqrt{in.}$
PT5-1A[a]	Air, 70° F	1.994 --	9.038 --	16.87 8.43	0.05 .05	10 2 500	0.1 1	-- 25.19	0.715 .730	2.650 2.670	0.730 .736	2.670 2.675	1 500 2	24.0 11.9	-- 40.9
PT5-2A	Air, 70° F	2.000 --	9.030 --	24.36 12.62	0 .05	1 2 500	0.1 1	-- 23.42	0.615 .790	2.580 3.800	0.790 .830	3.800 3.810	175 000 16	37.5 20.4	-- 43.6
PT5-3A	LN_2	1.980 --	9.075 --	16.92 8.46	0.05 .05	10 2 500	0.1 1	-- 24.21	0.643 .685	2.600 2.640	0.685 .690	2.640 2.640	4 200 2	23.3 11.7	-- 37.8
PT6-1	Air, 70° F	1.993 -- --	9.000 -- --	15.88 24.36 12.71	0.05 .05 .05	200 1 1 500	0.5 .1 1	-- -- 27.87	0.661 .753 .775	2.550 2.730 2.900	0.753 .775 .831	2.730 2.900 2.905	460 22 000 37	22.8 38.5 19.2	-- -- 52.2
PT6-2	LN_2	1.992 -- --	9.011 -- --	15.88 25.40 12.70	0.05 .05 .05	200 2 1 500	0.5 .1 1	-- -- 27.30	0.704 .812 .887	2.630 2.760 3.270	0.812 .887 .903	2.760 3.270 3.280	540 37 500 11	23.0 40.6 20.3	-- -- 51.0
PT6-3	LN_2	2.016 --	9.030 --	18.79 10.44	0.05 .05	10 2 500	0.1 1	-- 29.66	0.698 .732	2.640 2.660	0.732 .742	2.660 2.665	3 400 4	26.9 14.8	-- 49.8

[a]"A" in specimen number signifies specimen was postweld aged at 325° F for 24 hours.

Even though the fracture specimen geometry and failure stress levels were not completely satisfactory for generating valid plane strain fracture toughness data, the test results gave pertinent information on critical flaw sizes for thick welded plate. This information was important for estimating nondestructive inspection and proof test screening requirements. Essentially, the test results showed that for every case, the critical flaw size for failure was relatively large. For all unaged-weld-specimen tests at room temperature, the toughness was so high that the failure stress exceeded the weld yield strength. This was even true at LN_2 temperature for the EB and pulse GTA welds. However, for all aged-specimen tests, the failure stress was below the weld yield stress, which means that a proof test could be used to screen flaws in aged welds but not in unaged welds. However, the critical flaw sizes in unaged welds are so large that nondestructive inspection would be adequate for locating any that occur, particularly after the flaws have been opened up in a proof test.

Fatigue Crack Growth Tests

As mentioned previously, most of the fatigue crack growth rate tests were conducted by the application of low stress cycles, then higher stress cycles, then low stress cycles again. In some cases, usually where fatigue bands were difficult to distinguish, only single fatigue stress levels were applied. The appearances of the fatigue bands for the three types of welds are shown in figures 15 and 17. As can be seen, the EB weld fracture and fatigue surfaces had the most distinctive appearance. The fatigue surfaces were unusually smooth for weld material, and the fracture surfaces looked almost similar to glue-joint-type failures between bonded plates. The fatigue bands on the EB weld specimens were also the most visible and the easiest to measure accurately with a microscope. The growth of the fatigue cracks for discrete numbers of fatigue cycles was measured using the crack dimensions A and 2B represented by the distinctive bands. The results are shown in tables VIII, IX, and X. The experimental crack growth rate per cycle was then computed, and these results are shown as $(A_f - A_i)/N$ in the same tables along with the stress intensity factor range for each test.



(a) GMA welded specimen. (b) Pulse GTA welded specimen.

Figure 17. - Fracture face photographs of GMA and pulse GTA welded specimens.

To determine the stress intensity factor range in fatigue crack growth rate data analysis, equation (1) was put into the following form.

$$\Delta K_A = F\Delta\sigma\sqrt{\frac{\pi}{Q}\,\frac{A_i + A_f}{2}}\,M \tag{5}$$

where

$$Q = \Phi^2 - 0.212\left[\frac{\Delta\sigma/(1 - R)}{F_{TY}}\right]^2 \tag{6}$$

In equation (6), Irwin's original expression has been modified to account for cyclic loading at different values of R. The values of Φ^2 and F_{TY} used to calculate Q are the same as those used for determining K_{IC} from equation (4).

An examination of the fatigue crack growth results plotted in figures 18 to 22 shows that the growth rates are greatly accelerated by aging of the welds. This information correlates with the observed reduction in K_{IC} caused by postweld aging. Other observations with respect to the three types of welds are as follows.

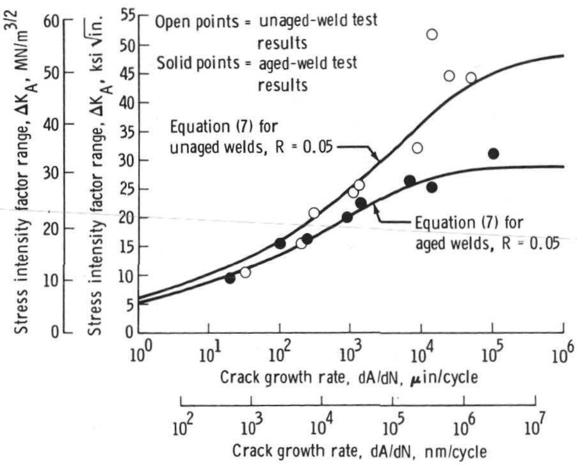


Figure 18. - Comparison of theoretical crack growth rate with experimental EB weld data for air environment.

1. The crack growth rates of EB welded and pulse GTA welded specimens were similar and varied only with the value of K_{IC} that was a function of heat treatment and test temperature.

2. The crack growth rate for GMA welds was generally greater than the growth rate of EB and pulse GTA welds.

3. As shown in figure 21, the growth rate of pulse GTA welded thick plate is the same as some previous unpublished results for GTA welded thin plate.

4. By comparing the weld results with 2219-T87 aluminum base metal results reported in reference 5, the conclusion is that fatigue crack growth rate in weld metal is significantly faster than in base metal.

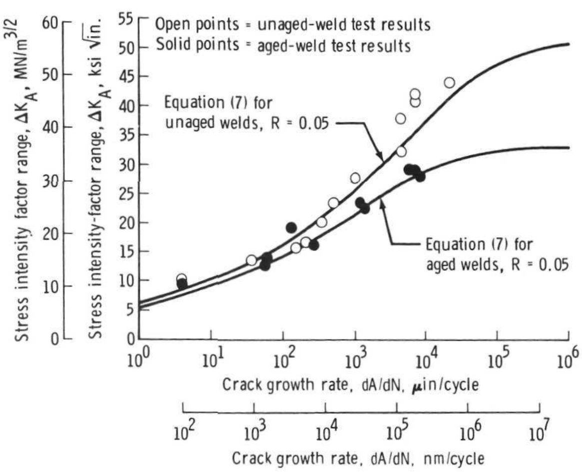


Figure 19. - Comparison of theoretical crack growth rate with experimental EB weld data for LN_2 environment.

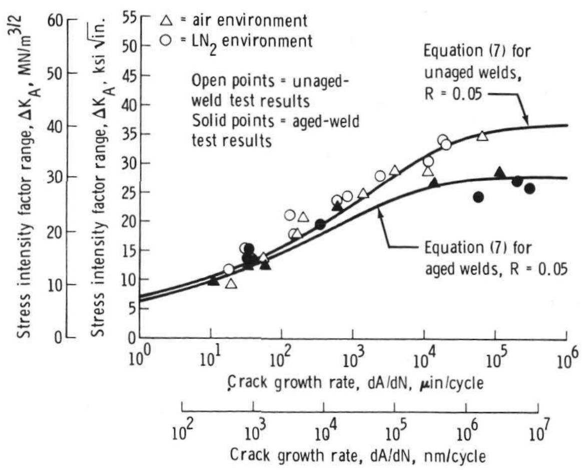


Figure 20. - Comparison of theoretical crack growth rate with experimental GMA weld data.

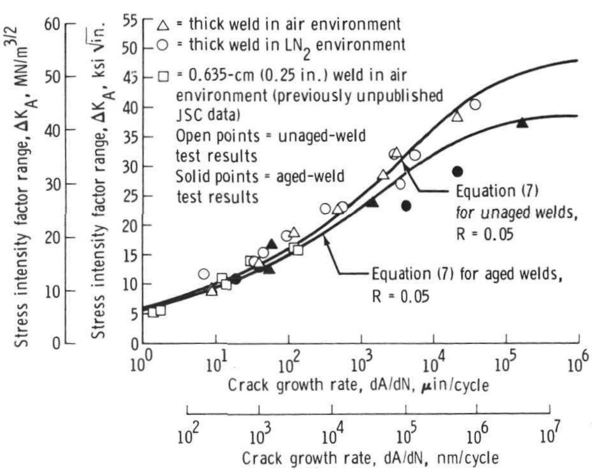


Figure 21. - Comparison of theoretical crack growth rate with experimental GTA weld data.

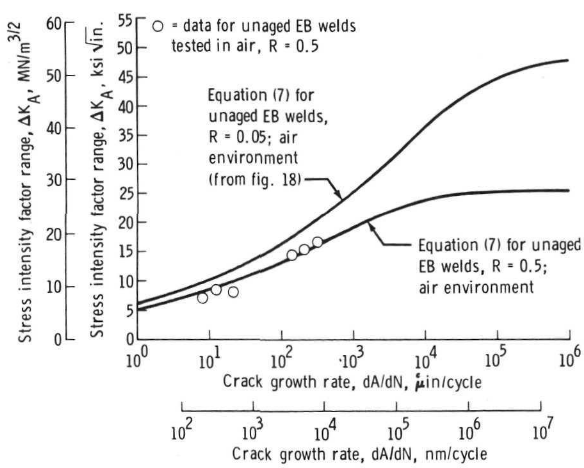


Figure 22. - Comparison of theoretical crack growth rate with experimental data for R = 0.5.

Correlation of Crack Growth Data With Analysis

Because fatigue crack growth rate is a complicated function of the stress intensity factor range ΔK plus other secondary effects, it is not easy to evaluate test data directly. The most useful evaluations are made by first correlating the test data with a crack growth rate equation. This procedure not only provides an analytical model but also gives information on the ability to calculate fatigue crack growth rate behavior accurately. This ability is imperative for developing an adequate fracture control plan for propellant tanks with welded joints.

The fatigue crack growth rate equation used to correlate with the experimental data was obtained from reference 6. This equation was earlier found to have good correlation with 2219-T87 aluminum base metal data, and the correlation was reported in reference 7. For the analysis of semielliptical surface-type flaws, the equation is expressed as follows.

$$\frac{dA}{dN} = \frac{\overline{CA}\left(\Delta K_A\right)^S}{(1 - R)K_{IC} - \Delta K_A} \tag{7}$$

Equation (7) was originally proposed for growth of through-the-thickness cracks in thin plates. The symbols have been changed in equation (7) and also in equations (1) to (6) to be consistent with the computer analysis described in reference 7.

For determining the empirical constants $\overline{CA}$ and S in equation (7), the equation was rewritten as follows.

$$\left[(1 - R)K_{IC} - \Delta K_A\right]\frac{dA}{dN} = \overline{CA}\left(\Delta K_A\right)^S \tag{8}$$

Equation (8) plots as a straight line on log-log coordinates and is referred to as the linearized form of equation (7). All crack growth rate test data from tables VIII, IX, and X were plotted into this linearized form using log-log coordinates, and the results are shown in figures 23 and 24. A straight line was then faired through the data points to derive the constants $\overline{CA}$ and S in equation (8). The reasonably good agreement between the faired straight line and the data points confirms the validity of equation (7).

The empirical constants that produced the most accurate curve fits are listed in table XI. In this table, the average values listed for K_{IC} were essentially obtained from table VII. The K_{IC} values for the EB welds were taken directly with no change. For the GMA and pulse GTA welds, the K_{IC} values at room and LN_2 temperatures were so similar that an average was used for both temperatures. Also, because the toughness of GMA weld material would be less than the average values shown in table VII (because of the GTA weld root), a minimum value was selected from the listed data. The reason for the selection was that the lower toughness values occurred for the smallest flaws that were completely in GMA weld metal. Making this change improved the fit of the data in figure 24 with the straight-line relationship.

Also shown in figure 23 are upper and lower bounds for the empirical constant $\overline{CA}$. The difference between the best fit and limit values for $\overline{CA}$ is approximately a factor of four. These values indicate, then, that a scatter factor of four is required for crack growth rate analysis of welded aluminum plate.

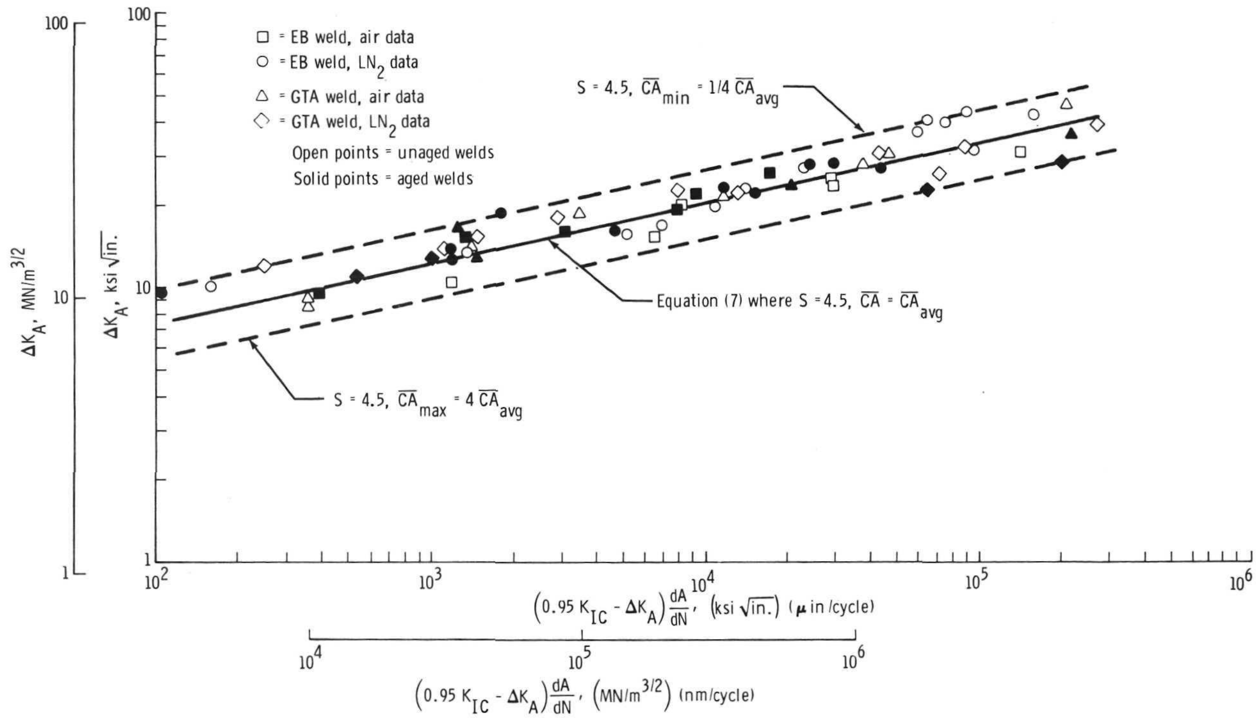


Figure 23.- Comparison of theoretical crack growth rate (linearized) with experimental EB weld and pulse GTA weld data.

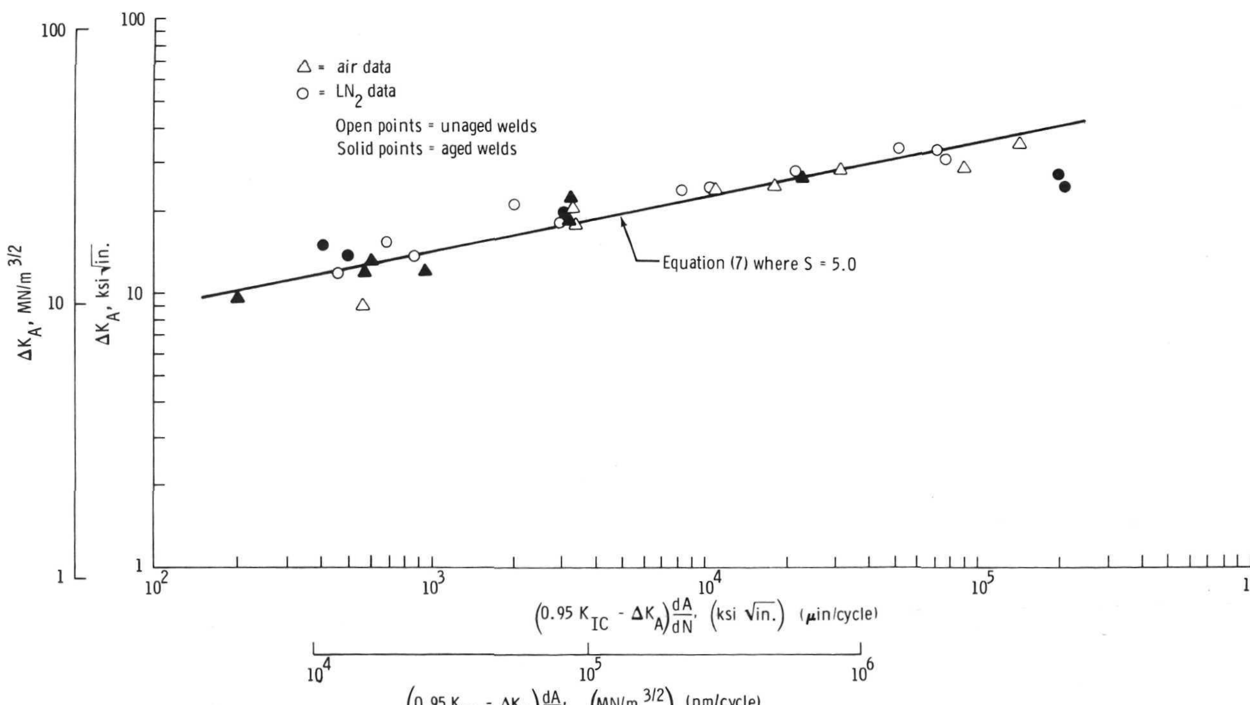


Figure 24.- Comparison of theoretical crack growth rate (linearized) with experimental GMA weld data.

TABLE XI. - VALUE OF CONSTANTS IN EQUATION (7)

Type weld and fatigue environment	S	K_{IC}		$\overline{CA}$		
		$MN/m^{3/2}$	ksi $\sqrt{in.}$	$\frac{nm/cycle}{(MN/m^{3/2})^{S-1}}$	$\frac{\mu in/cycle}{(ksi \sqrt{in.})^{S-1}}$	$\frac{in/cycle}{(psi \sqrt{in.})^{S-1}}$
Unaged EB weld in air	4.5	55.7	50.7	0.213	0.0117	0.37×10^{-18}
Unaged EB weld in LN_2	4.5	59.3	54.0	.213	.0117	$.37 \times 10^{-18}$
Aged EB weld in air	4.5	33.5	30.5	.213	.0117	$.37 \times 10^{-18}$
Aged EB weld in LN_2	4.5	38.5	35.0	.213	.0117	$.37 \times 10^{-18}$
Unaged GTA weld in air and LN_2	4.5	55.5	50.5	.213	.0117	$.37 \times 10^{-18}$
Aged GTA weld in air and LN_2	4.5	44.8	40.8	.213	.0117	$.37 \times 10^{-18}$
Unaged GMA weld in air and LN_2	5.0	42.8	39.0	.035	.002	$.2 \times 10^{-20}$
Aged GMA weld in air and LN_2	5.0	32.4	29.5	.035	.002	$.2 \times 10^{-20}$

In figures 18 to 22, the correlation is shown between experimental and theoretical crack growth rates for each type of weld. The first four of these figures are for the comparisons with test data having the load ratio R equal to 0.05. The last one, figure 22, is for a comparison with the load ratio R equal to 0.5. Unfortunately, the scatter in the data is very significant, which is often typical for flaw growth in welds; but the results do indicate that equation (7) is acceptable for analyzing crack growth rate in welded 2219-T87 material.

LONGITUDINAL WELD SPECIMEN RESULTS

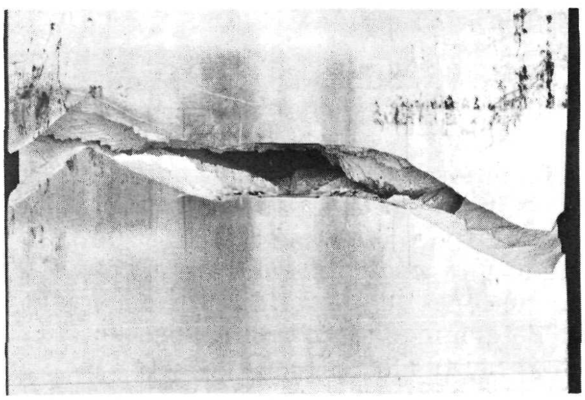
The previously discussed cross-weld specimen tests gave information on basic weld properties and flaw growth behavior for flaws in a direction parallel to the weld (representative of lack-of-fusion cracks). However, flaws often occur that are in a direction perpendicular to the weld. An example of this would probably be a weld shrinkage crack. To study this problem, the single longitudinal weld specimen (weld parallel to direction of load) was tested in air to determine the growth characteristics for a flaw in a direction normal to the weld. The results of this test are listed in table XII. A photograph of the fractured specimen is shown in figure 25. A curve of crack extension compared to number of load cycles is shown in figure 26.

TABLE XII. - CRACK GROWTH TEST RESULTS FOR LONGITUDINAL EB WELDED SPECIMEN[a] OF 2219-T87 ALUMINUM ALLOY

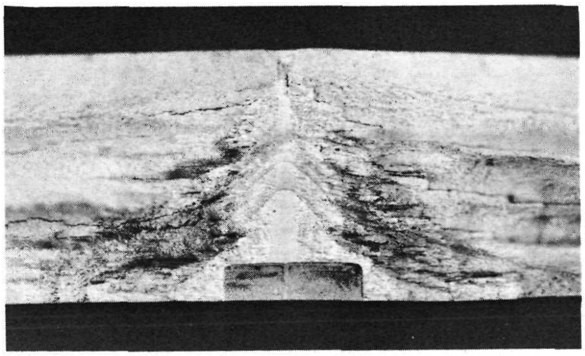
Number load cycles	Accumulative load cycles	Stress range, $\Delta\sigma$, MN/m^2 (ksi)	Stress ratio, R	Final flaw size	
				A_f, cm (in.)	$2B_f$, cm (in.)
0	0			1.24 (0.49)	4.06 (1.60)
600	600	207 (30.0)	0.05	1.30 (.51)	4.37 (1.72)
1	601	320 (46.4)	0	1.35 (.53)	4.70 (1.85)
1776	2 377	207 (30.0)	.05	1.47 (.58)	4.95 (1.95)
1	2 378	303 (43.9)	0	1.52 (.60)	5.00 (1.97)
3013	5 391	207 (30.0)	.05	2.16 (.85)	5.92 (2.33)
1	5 392	312 (45.3)	0	2.18 (.86)	6.02 (2.37)
2573	7 965	207 (30.0)	.05	2.69 (1.06)	7.21 (2.84)
1	7 966	299 (43.3)	0	2.72 (1.07)	7.29 (2.87)
1100	9 066	207 (30.0)	.05	3.28 (1.29)	8.00 (3.15)
1	9 067	292 (42.4)	0	3.30 (1.30)	8.00 (3.15)
1270	10 337	207 (30.0)	.05	4.01 (1.58)	9.07 (3.57)
[b]1	10 338	306 (44.4)	0		

[a]Specimen dimensions: 4.919 centimeters (1.937 in.) thick, 23.01 centimeters (9.061 in.) wide, and 84 centimeters (33 in.) long.

[b]Specimen fractured.



(a) Front view.



(b) Fracture face.

Figure 25. - Fracture appearance of longitudinal EB weld specimen.

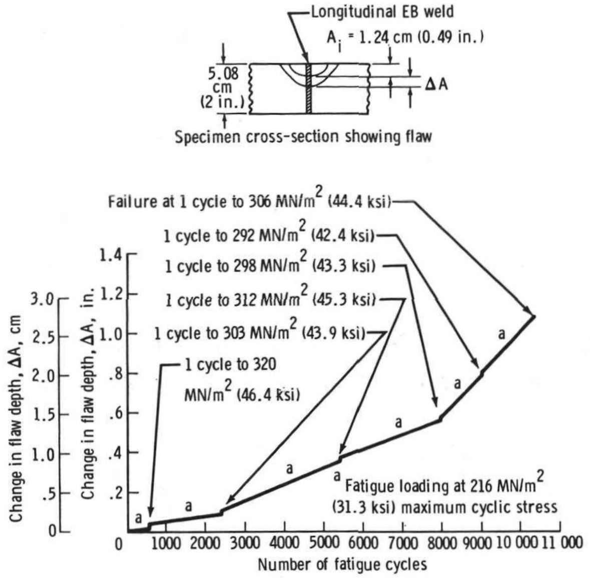


Figure 26. - Change in flaw depth compared to number of fatigue cycles for longitudinal EB weld specimen.

The results of the longitudinal weld specimen test show that a flaw growing perpendicular to an EB weld in a thick 2219-T87 aluminum plate would be difficult to analyze using fracture mechanics theory. Because of base-material delamination at the crack front when an attempt was made to load the specimen to failure, difficulty was experienced both in conducting the test and in analyzing the results. Crack front delamination is fairly common for 2219-T87 aluminum base material when tested in air at room or elevated temperatures. When delamination occurs, crack growth is retarded both for static loading and for fatigue loading. In the test of the longitudinal weld specimen, five attempts were made to load the specimen to failure before failure actually occurred. In each attempt, the specimen was subjected to the maximum load capacity of the test machine and required additional fatigue loading to increase the flaw size for ultimate failure. The test results indicate that a flaw in a direction perpendicular to an EB weld in 2219-T87 aluminum would have to be many times longer than the width of the weld to cause failure at operating or proof stress levels. Also, the use of a proof test to ascertain minimum cyclic life at operating stress levels would give significantly conservative results because of crack retardation when delamination occurs. Compared with the growth rates for the cross-welded specimens, the data from the longitudinal weld specimen showed much slower crack growth rates.

CONCLUSIONS

The results of the test program to investigate fracture toughness and flaw growth behavior in thick welded plates of 2219-T87 aluminum alloy can be summarized as follows.

1. The welding of 6.35-centimeter (2.5 in.) thick 2219-T87 aluminum plate is feasible, but the weld parameters need better definition.

2. Aging the welds at 436° K (325° F) for 24 hours increased the tensile yield strength of the welds but significantly decreased the fracture toughness.

3. In the as-welded condition, the electron beam and pulse current gas tungsten arc welds have higher toughness values than gas metal arc welds. After aging, the pulse current gas tungsten arc welds have higher toughness than either the electron beam or gas metal arc welds.

4. The fatigue crack growth rate for weld metal was generally greater than for parent metal.

5. The fatigue crack growth rate experimental data correlated satisfactorily with analytical results from equation (7).

6. From the limited amount of data available, the fatigue crack growth rate of pulse current gas tungsten arc welded thick plate was the same as the rate for gas tungsten arc welded thin plate.

7. For cracks that are perpendicular to a longitudinal weld, extensive delamination occurs at the crack front, and fracture mechanics analysis becomes conservative.

8. The critical flaw sizes in the welds are relatively large and would be readily discernible by existing inspection techniques.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, May 2, 1973
986-15-31-01-72

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APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The SI was adopted by the Eleventh General Conference on Weights and Measures in Paris during October 1960, in Resolution Number 12.

TABLE A-I. - CONVERSION FACTORS FOR SI UNITS

To convert from U.S. customary units	Multiply by —	To obtain SI units
lbf	4.448222	newtons (N)
in.	2.54×10^{-2}	meters (m)
kips per square inch (ksi)	6.894757×10^{6}	newtons/meter^2 (N/m^2)
ksi$\sqrt{\text{in.}}$	1.0988	MN/m$^{3/2}$
μin/cycle	25.4	nm/cycle

TABLE A-II. - PREFIXES AND SYMBOLS TO INDICATE MULTIPLES OF UNITS

Multiple	Prefix	Symbol
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{6}	mega	M
10^{9}	giga	G

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